groundwater QUALITY PROTECTION

a guide for water utilities, municipal authorities, and environment agencies

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THE WORLD BANK

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Groundwater Management Advisory Team (GW•MATE)
in association with the Global Water Partnership
co-sponsored by WHO-PAHO-CEPIS & UNESCO-ROSTLAC-PHI

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Contents

Forewords

This is a much welcomed publication that provides clear guidance to water-sector decision makers, planners, and practioners on how to deal with the quality dimension of groundwater resources management in the World Bank's client countries. It is very timely, since there is growing evidence of increasing pollution threats to groundwater and some well-documented cases of irreversible damage to important aquifers, following many years of widespread public policy neglect.

The idea to undertake such a review came from Carl Bartone and Abel Mejia of the World Bank, following an initial attempt to draw attention to the need for groundwater protection in the Latin American-Caribbean Region by the WHO-PAHO Centre for Sanitary Engineering & Environmental Science (CEPIS), who together with the UNESCO-IHP Regional Office for Latin American-Caribbean Region have provided support for this new initiative.

The publication has been prepared for a global target audience under the initiative of the World Bank's Groundwater Management Advisory Team (GW-MATE), which works in association with the Global Water Partnership, under the coordination of the GW-MATE leader, Dr. Stephen Foster. It is practically based in a review of the last decade's experience of groundwater protection in Latin America and of concomitant advances in the European Union and North America. Following the approaches advocated will help make groundwater more visible at the policy level and in civil society.

John Briscoe
World Bank Senior Water Adviser

This Guide has been produced in the belief that groundwater pollution hazard assessment must become an essential part of environmental best practice for water supply utilities. Such assessments should lead to a clearer appreciation of priority actions required of municipal authorities and environmental regulators to protect groundwater, both in terms of avoiding future pollution and mitigating threats posed by existing activities. In the majority of cases the cost of these actions will be modest compared to that of developing new water supply sources and linking them into existing water distribution networks.

The situation in some Latin American countries has become critical, in part because many of the aquifers providing many municipal water supplies are experiencing serious overdraft and/or increasing pollution. Among the cities of the region that are highly dependent upon groundwater resources, are Recife in Brazil, Lima in Peru, numerous Mexican cities, and most of the Central American capitals.

The Guide is thus particularly relevant for the World Bank's Latin American and Caribbean Region, where many countries have initiated major changes to modernize their institutional and legal framework for water resources management, but may not yet have considered groundwater at the same level as surface water, because of lack of awareness and knowledge of groundwater issues and policy options. A process of specialist consultation informed the present work, and came out with the recommendation that the Guide should focus on one technique for each component of groundwater pollution hazard assessment in the interest of clarity and consistency for the average user.

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Four meetings in Latin America represented key steps in undertaking the systematic assessment of relevant experience in that region and in reviewing the substantive content of this Guide. The following are acknowledged for their support and input to the respective meetings:

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Dedication

The authors wish to dedicate this Guide to the memory of Professor Mario Fili of the Universidad Nacional del Litoral-Facultad de Ingenieria y Ciencias Hidricas, Santa Fe-Argentina, who died prematurely during the project. Mario was one of the leading groundwater specialists of Argentina and Latin America, author of some 70 published technical papers and articles, a life-long professional friend of the first author and much-loved professor and colleague of two other authors of this Guide.

PART A: EXECUTIVE OVERVIEW

Rationale for Groundwater Protection

An Executive Overview for senior personnel of water service companies, municipal authorities, and environment agencies, answering anticipated questions about groundwater pollution threats and protection needs, and providing essential background and standardized approaches to adopt in compliance with their duty to safeguard the quality of water destined for public supply.

Rationale for Groundwater Protection

1. Why has this *Guide* been written?

- At the broad scale, groundwater protection strategies (and their prerequisite pollution hazard assessment) have to be promoted by the water or environmental regulator (or that agency, department, or office of national, regional, or local government charged with performing this function). It is important, however, that attention is focused at the scale and level of detail of the assessment and protection of specific water supply sources.
- All too widely in the past, groundwater resources have, in effect, been abandoned to chance. Often those who depend on such resources for the provision of potable water supplies have taken no significant action to assure raw-water quality, nor have they made adequate efforts to assess potential pollution hazard.
- Groundwater pollution hazard assessments are needed to provide a clearer appreciation of the actions needed to protect groundwater quality against deterioration. If undertaken by water supply utility companies, it is hoped that, in turn, both preventive actions to avoid future pollution, and corrective actions to control the pollution threat posed by existing and past activities, will be realistically prioritized and efficiently implemented by the corresponding municipal authorities and environmental regulators.

2. Why do groundwater supplies merit protection?

- Groundwater is a vital natural resource for the economic and secure provision of potable water supply in both urban and rural environments, and plays a fundamental (but often little appreciated) role in human well-being, as well as that of many aquatic ecosystems.
- Worldwide, aquifers (geological formations containing useable groundwater resources) are experiencing an increasing threat of pollution from urbanization, industrial development, agricultural activities, and mining enterprises.
- Thus proactive campaigns and practical actions to protect the (generally excellent) natural quality of groundwater are widely required, and can be justified on both broad environmental sustainability and narrower economic-benefit criteria.
- In the economic context, it is also important that water companies make assessments of the strategic value of their groundwater sources. This should be based on a realistic evaluation of their replacement value, including both the cost of developing the new supply source and

also (most significantly) the cost of connecting and operating increasingly distant sources into existing distribution networks.

- Special protection measures are (in fact) needed for all boreholes, wells, and springs (both public and private) whose function is to provide water to potable or equivalent standards. This would thus include those used as bottled mineral waters and for food and drink processing.
- For potable mains water supply, a high and stable raw water quality is a prerequisite, and one that is best met by protected groundwater sources. Recourse to treatment processes (beyond precautionary disinfection) to achieve this end should be regarded as a last-resort, in view of their technical complexity and financial cost, and the operational burden they impose.

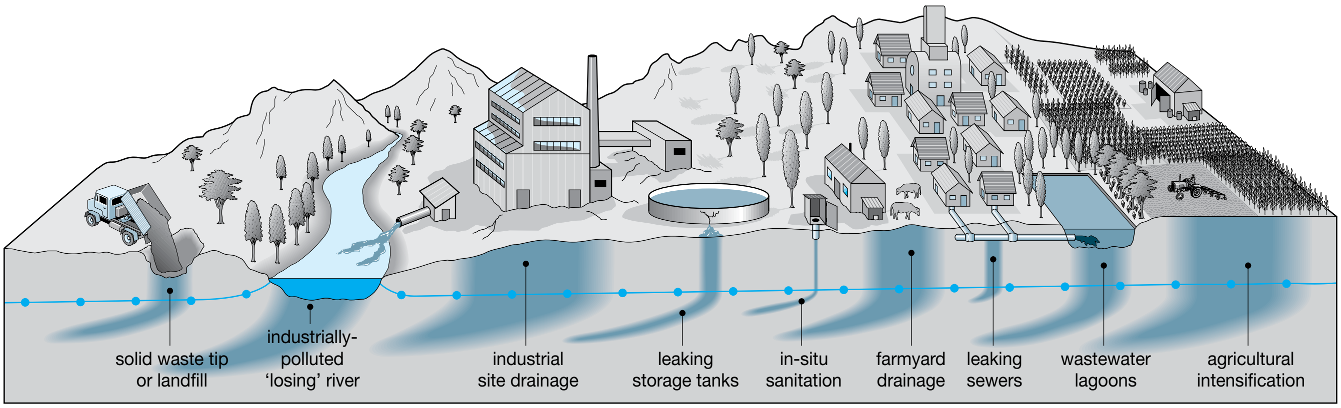
3. What are the common causes of groundwater quality deterioration?

- There are various potential causes of quality deterioration in an aquifer and/or in a groundwater supply. These are classified by genesis and further explained in Table A.1. In this Guide we are primarily concerned with protection against aquifer pollution and wellhead contamination, but it is necessary to be aware that other processes can also be operative.

Table A.1 Classification of groundwater quality problems

TYPE OF PROBLEM	UNDERLYING CAUSE	CONTAMINANTS OF CONCERN
AQUIFER POLLUTION	inadequate protection of vulnerable aquifers against manmade discharges and leachates from urban/industrial activities and intensification of agricultural cultivation	pathogens, nitrate or ammonium, chloride, sulphate, boron, arsenic, heavy metals, dissolved organic carbon, aromatic and halogenated hydrocarbons, certain pesticides
WELLHEAD CONTAMINATION	inadequate well design/construction allowing direct ingress of polluted surface water or shallow groundwater	mainly pathogens
Saline Intrusion	saline (and sometimes polluted) groundwater induced to flow into freshwater aquifer as result of excessive abstraction	mainly sodium chloride, but can also include persistent manmade contaminants
Naturally Occurring Contamination	related to chemical evolution of groundwater and solution of minerals (can be aggravated by manmade pollution and/or excessive abstraction)	mainly soluble iron and fluoride, sometimes magnesium sulphate, arsenic, manganese, selenium, and other inorganic species

Figure A.1
Common processes of groundwater pollution



4. How do aquifers become polluted?

- Most groundwater originates as excess rainfall infiltrating (directly or indirectly) at the land surface. In consequence, activities at the land surface can threaten groundwater quality. The pollution of aquifers occurs where the subsurface contaminant load generated by manmade discharges and leachates (from urban, industrial, agricultural, and mining activities) is inadequately controlled, and in certain components exceeds the natural attenuation capacity of the overlying soils and strata (Figure-A.1).
- Natural subsoil profiles actively attenuate many water pollutants, and have long been considered potentially effective for the safe disposal of human excreta and domestic wastewater. The auto-elimination of contaminants during subsurface transport in the vadose (unsaturated) zone is the result of biochemical degradation and chemical reaction, but processes of contaminant retardation due to sorption phenomena are also of importance, since they increase the time available for processes resulting in contaminant elimination.
- However, not all subsoil profiles and underlying strata are equally effective in contaminant attenuation, and aquifers will be particularly vulnerable to pollution where, for example, consolidated highly fissured rocks are present. The degree of attenuation will also vary widely with types of pollutant and polluting process in any given environment.
- Concern about groundwater pollution relates primarily to the so-called unconfined or phreatic aquifers, especially where their vadose zone is thin and water-table shallow, but significant pollution hazard may also be present even where aquifers are semi-confined, if the confining aquitards are relatively thin and permeable.
- An idea of the more common types of activity capable of causing significant groundwater pollution and the most frequently encountered contaminant compounds can be gained from Table A.2. It is important to recognize that these depart widely from the activities and compounds most commonly polluting surface water bodies, given the completely different controls governing the mobility and persistence of contaminants in the respective water systems.

Table A.2 Common groundwater contaminants and associated pollution sources

POLLUTION SOURCE	TYPE OF CONTAMINANT
Agricultural Activity	nitrates; ammonium; pesticides; fecal organisms
In-situ Sanitation	nitrates; halogenated hydrocarbons; microorganisms
Gas Stations and Garages	aromatic hydrocarbon; benzene; phenols; halogenated hydrocarbons
Solid Waste Disposal	ammonium; salinity; halogenated hydrocarbons; heavy metals
Metal Industries	trichloroethylene; tetrachloroethylene; halogenated hydrocarbons; phenols; heavy metals; cyanide
Painting and Enamel Works	alkylbenzene; halogenated hydrocarbons; metals; aromatic hydrocarbons; tetrachloroethylene
Timber Industry	pentachlorophenol; aromatic hydrocarbons; halogenated hydrocarbons
Dry Cleaning	trichloroethylene; tetrachloroethylene
Pesticide Manufacture	halogeneted hydrocarbons; phenols; arsenic
Sewage Sludge Disposal	nitrates; halogenated hydrocarbons; lead; zinc
Leather Tanneries	chromium; halogeneted hydrocarbons; phenols
Oil and Gas Exploration/Extraction	salinity (sodium chloride); aromatic hydrocarbons
Metalliferous and Coal Mining	acidity; various heavy metals; iron; sulphates

- It is also important to stress that certain activities (and specific processes or incremental practices within such activities) often present disproportionately large threats to groundwater quality. Thus sharply focused and well-tuned pollution control measures can produce major benefits for relatively modest cost.
- Human activity at the land surface modifies aquifer recharge mechanisms and introduces new ones, changing the rate, frequency, and quality of groundwater recharge. This is especially the case in arid climates, but also pertains in more humid regions. Understanding of these mechanisms and diagnosis of such changes are critical in the assessment of groundwater pollution hazard.
- Water movement and contaminant transport from the land surface to aquifers can in many cases be a slow process. It may take years or decades before the impact of a pollution episode by a persistent contaminant becomes fully apparent in groundwater supplies, especially those abstracted from deeper wells. This factor can simultaneously be a valuable benefit and a serious concern because:

- it allows time for the breakdown of degradable contaminants
- it may lead to complacency about the likelihood of penetration of persistent contaminants.

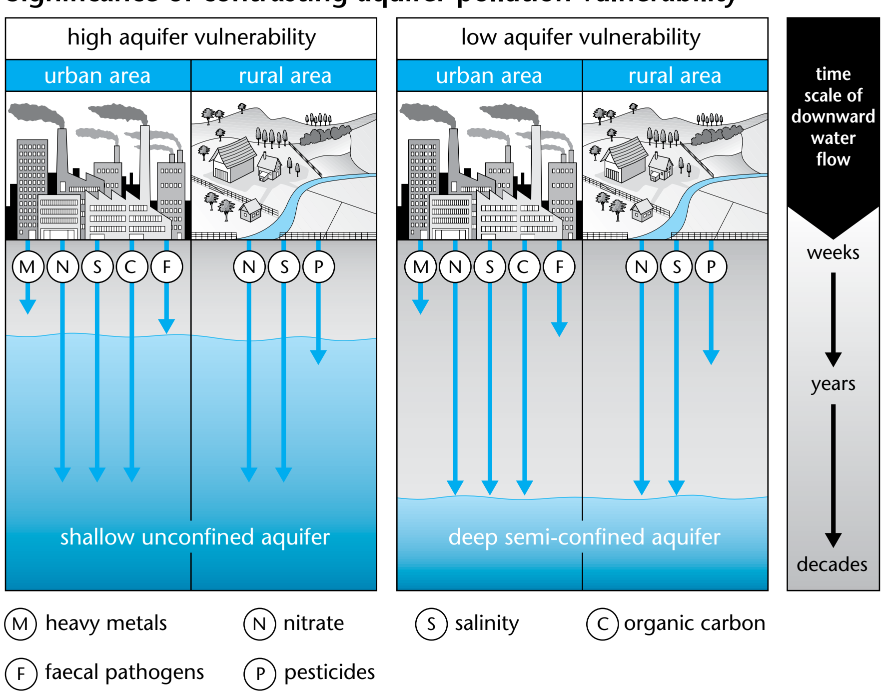
The implication is also that once groundwater quality has become obviously polluted, large volumes of the aquifer are usually involved. Clean-up measures, therefore, nearly always have a high economic cost and are often technically problematic.

5. How can groundwater pollution hazard be assessed?

- The most logical approach to groundwater pollution hazard is to regard it as the interaction between:
  - the aquifer pollution vulnerability, consequent upon the natural characteristics of the strata separating it from the land surface
  - the contaminant load that is, will be, or might be, applied on the subsurface environment as a result of human activity.

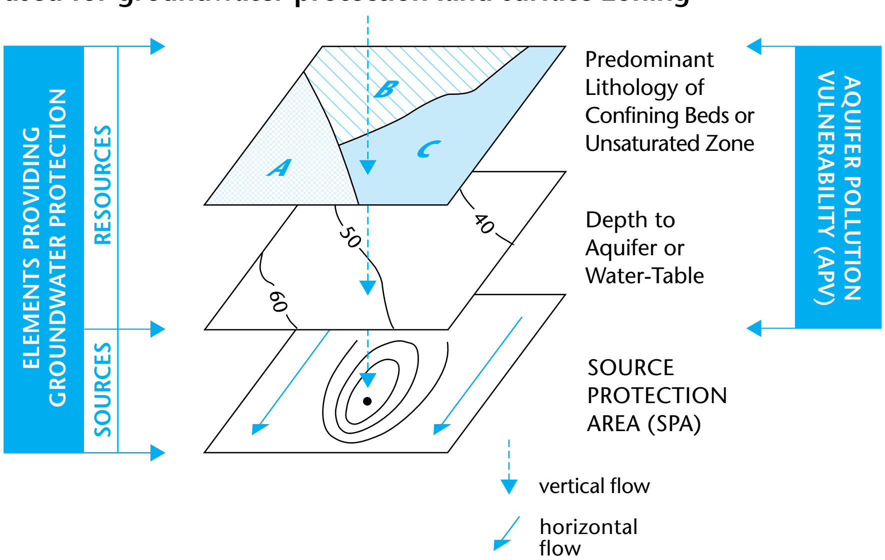
  Adopting such a scheme, we can have high vulnerability but no pollution hazard, because of the absence of significant subsurface contaminant load and vice versa. Both are perfectly consistent in practice. Moreover, contaminant load can be controlled or modified, but aquifer vulnerability is essentially fixed by the natural hydrogeological setting.
- The term aquifer pollution vulnerability is intended to represent sensitivity of an aquifer to being adversely affected by an imposed contaminant load (Figure A.2). In effect, it is the inverse of "the pollutant assimilation capacity of a receiving water body" in the jargon of river quality management.

Figure A.2
Significance of contrasting aquifer pollution vulnerability



- Aquifer pollution vulnerability can be readily mapped. On such maps the results of surveys of potential subsurface contaminant load can be superimposed, to facilitate the assessment of groundwater pollution hazard. The term groundwater resource pollution hazard relates to the probability that groundwater in an aquifer will become contaminated to concentrations above the corresponding WHO guideline value for drinking-water quality.
- Whether this hazard will result in a threat to groundwater quality at a given public-supply source depends primarily on its location with respect to the groundwater capture area of the source, and secondarily on the mobility and dispersion of the contaminant(s) concerned within the local groundwater flow regime. The assessment of groundwater supply pollution hazard can be undertaken by superimposing the supply protection perimeters on the aquifer vulnerability (Figure A.3), and subsequently relating the zones thus defined to summary maps derived from the inventory of potential subsurface contaminant load. It should be noted, however, that assessing the risk that such a hazard represents in terms of the resultant contaminant exposure for water users or in terms of increased water treatment costs are outside the scope of this Guide.
- The scales at which survey and mapping of the various components that are needed to assess groundwater pollution hazard are undertaken varies significantly with the main focus of the work—water supply protection or aquifer resource protection (Figure A.4), and this is discussed further below.

Figure A.3
Components of groundwater pollution hazard assessment used for groundwater protection land surface zoning

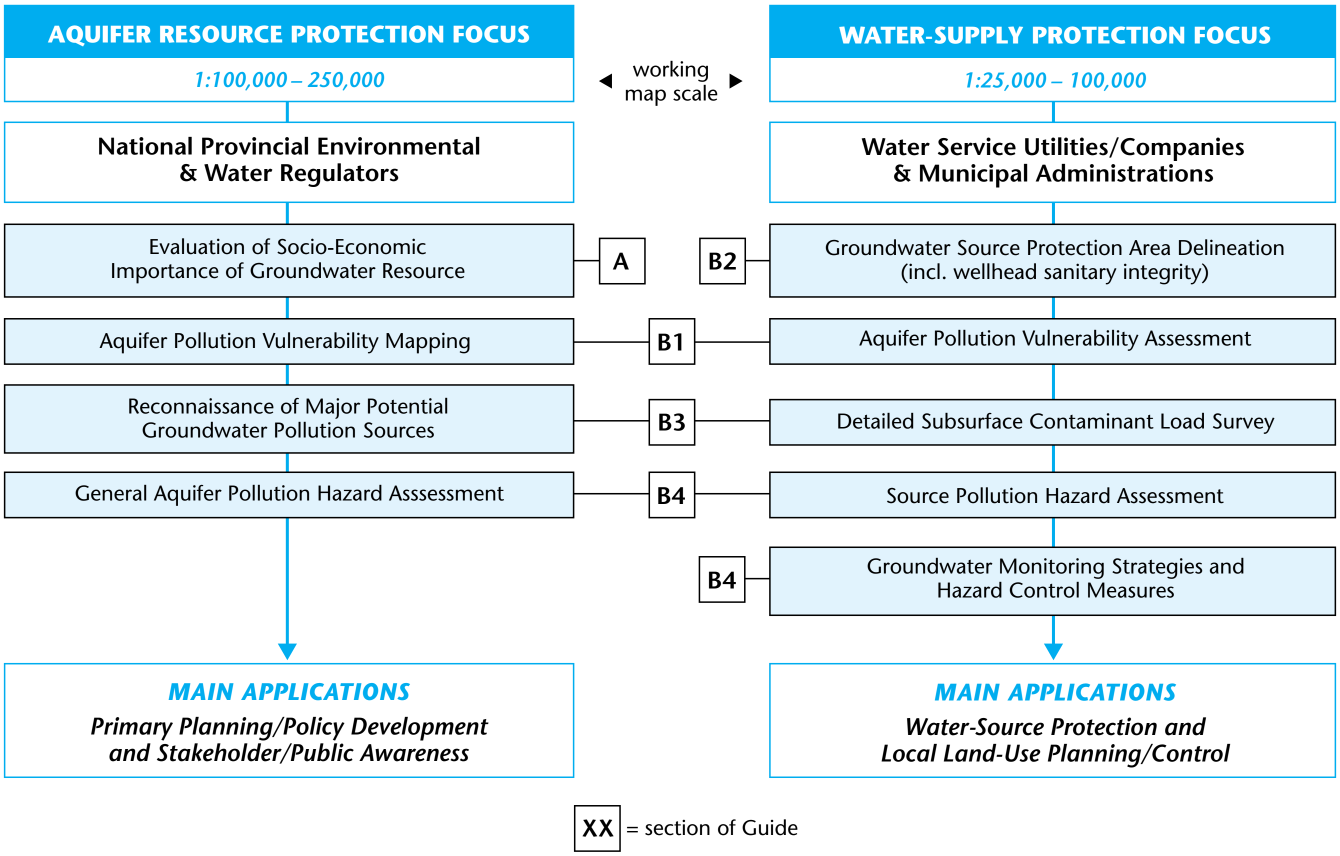


6. What does groundwater pollution protection involve?

- To protect aquifers against pollution it is necessary to constrain—both existing and future—land-use, effluent discharge, and waste disposal practices. It is possible to manage land entirely in the interest of groundwater gathering, and there are a few isolated European cases

Figure A.4

Focus and application of different levels of groundwater pollution hazard assessment



of water supply companies owning entire recharge areas primarily to prevent pathogenic (microbiological) contamination of groundwater supplies. This, however, is not generally acceptable on socioeconomic grounds, and it is normally necessary to define groundwater protection strategies that accept trade-offs between competing interests.

- Instead of applying universal controls over land use and effluent discharge to the ground, it is more cost-effective (and less prejudicial to economic development) to utilize the natural contaminant attenuation capacity of the strata overlying the aquifer, when defining the level of control necessary to protect groundwater quality. Simple and robust zones (based on aquifer pollution vulnerability and source protection perimeters) need to be established, with matrices that indicate what activities are possible and where they are at an acceptable risk to groundwater.
- Some may argue that hydrogeological conditions are so complex in detail that no zoning scheme will encapsulate them. However, there is an overriding case for land-surface zoning as a general framework for the development and implementation of groundwater protection policy because:
  - decisions will be made affecting groundwater in any event, and if planners have no zoning, this will mean less (not more) consultation with those concerned with water resources
  - it is unrealistic to expect exclusive protection for all groundwater; a zoning strategy is

important to ensure that trade-offs between economic development and aquifer protection are made objectively.

- Groundwater protection zoning also has a key role in setting priorities for groundwater quality monitoring, environmental audit of industrial premises, pollution control within the agricultural advisory system, and in public education generally. All of these activities are essential components of a comprehensive strategy for groundwater quality protection.

7. Why distinguish between groundwater resource and supply protection?

- A sensible balance needs to be struck between the protection of groundwater resources (aquifers as a whole) and specific sources (boreholes, wells, and springs). While both approaches to groundwater pollution control are complementary, the emphasis placed on one or the other will depend on the resource development situation and on the prevailing hydrogeological conditions.
- If potable use comprises only a minor part of the total available groundwater resource, then it may not be cost-effective to protect all parts of an aquifer equally. Source-oriented strategies will then be appropriate and will involve work at scales in the range 1:25,000–100,000, commencing with the delineation of the groundwater capture area of water supply sources (Figure A.5), and then including assessment of aquifer pollution vulnerability and subsurface contaminant load in the areas so defined.
- This approach is best suited to the more uniform, unconsolidated aquifers exploited only by a

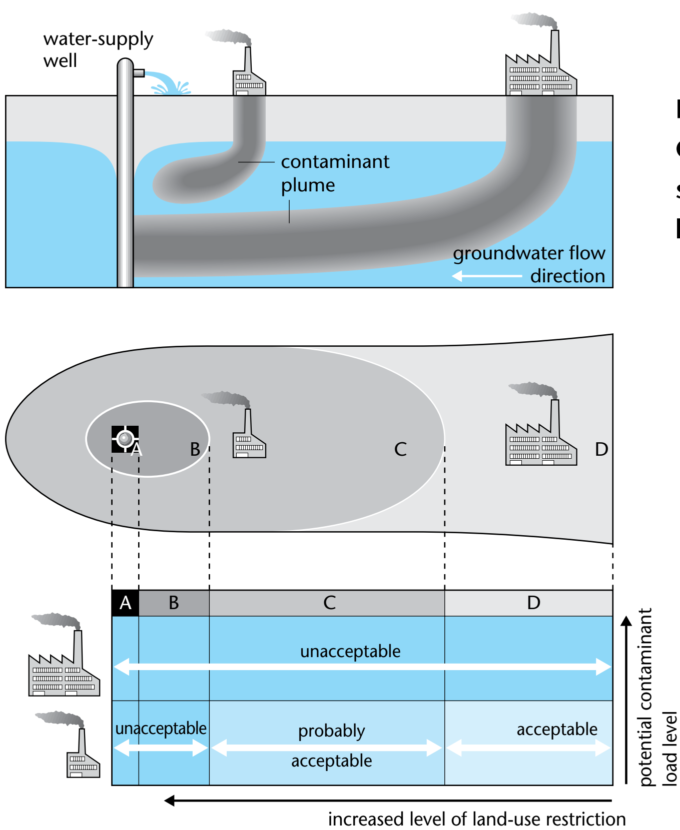


Figure A.5
Concept of groundwater source protection areas with land-use restrictions

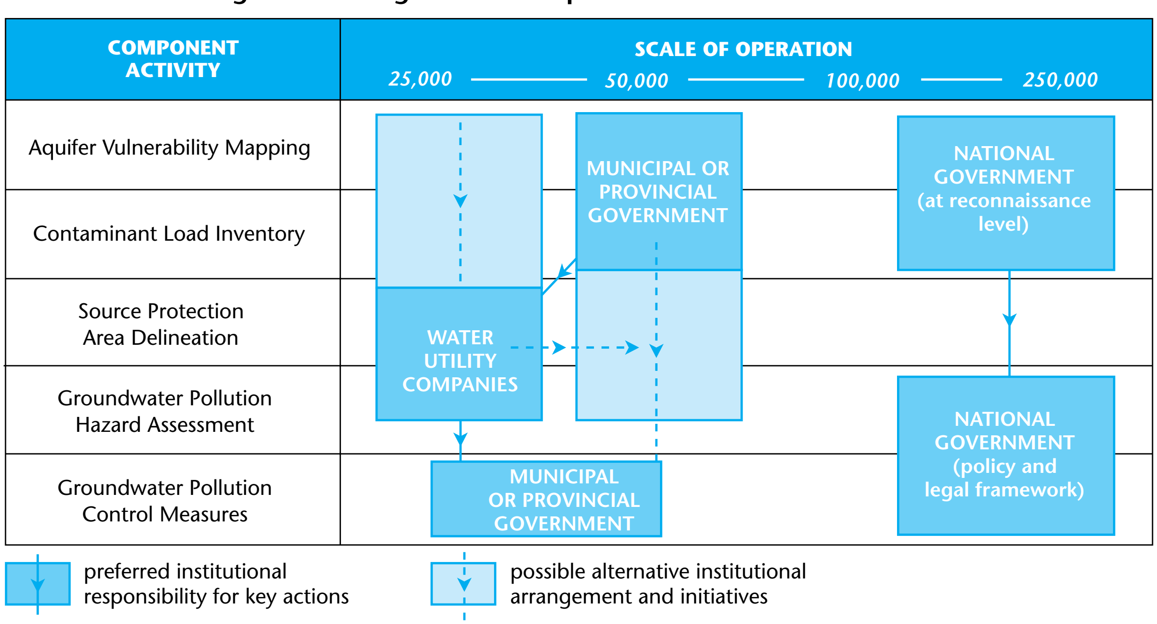
relatively small and fixed number of high-yielding municipal water supply boreholes with stable pumping regimes. It is most appropriate in the less densely populated regions where their delineation can be conservative without producing conflict with other interests. They cannot be so readily applied where there are very large and rapidly growing numbers of individual abstractions, which render consideration of individual sources and the establishment of fixed zones impracticable, and a broader approach needs to be taken.

- Aquifer-oriented strategies are more universally applicable, since they endeavour to achieve a degree of protection for the entire groundwater resource and for all groundwater users. They would commence with aquifer pollution vulnerability mapping of more extensive areas (including one or more important aquifers) working at a scale of 1:100,000 or more if the interest was limited to general information and planning purposes. Such mapping would normally be followed by an inventory of subsurface contaminant load at a more detailed scale, at least in the more vulnerable areas.

8. Who should promote groundwater pollution protection?

- The possible institutional options for the promotion of groundwater protection are summarized in Figure A.6. Given the responsibility of water-service companies to conform to codes and norms of sound engineering practice, there is an obligation on them to be proactive in undertaking or promoting pollution hazard assessments for all their groundwater sources. This will provide a sound basis for representations to be made to the local environment and water resource regulator for action on protection measures where needed. Even where no adequate pollution control legislation or agency exists, it will normally be possible for the

Figure A.6
Institutional arrangements for groundwater pollution evaluation and control



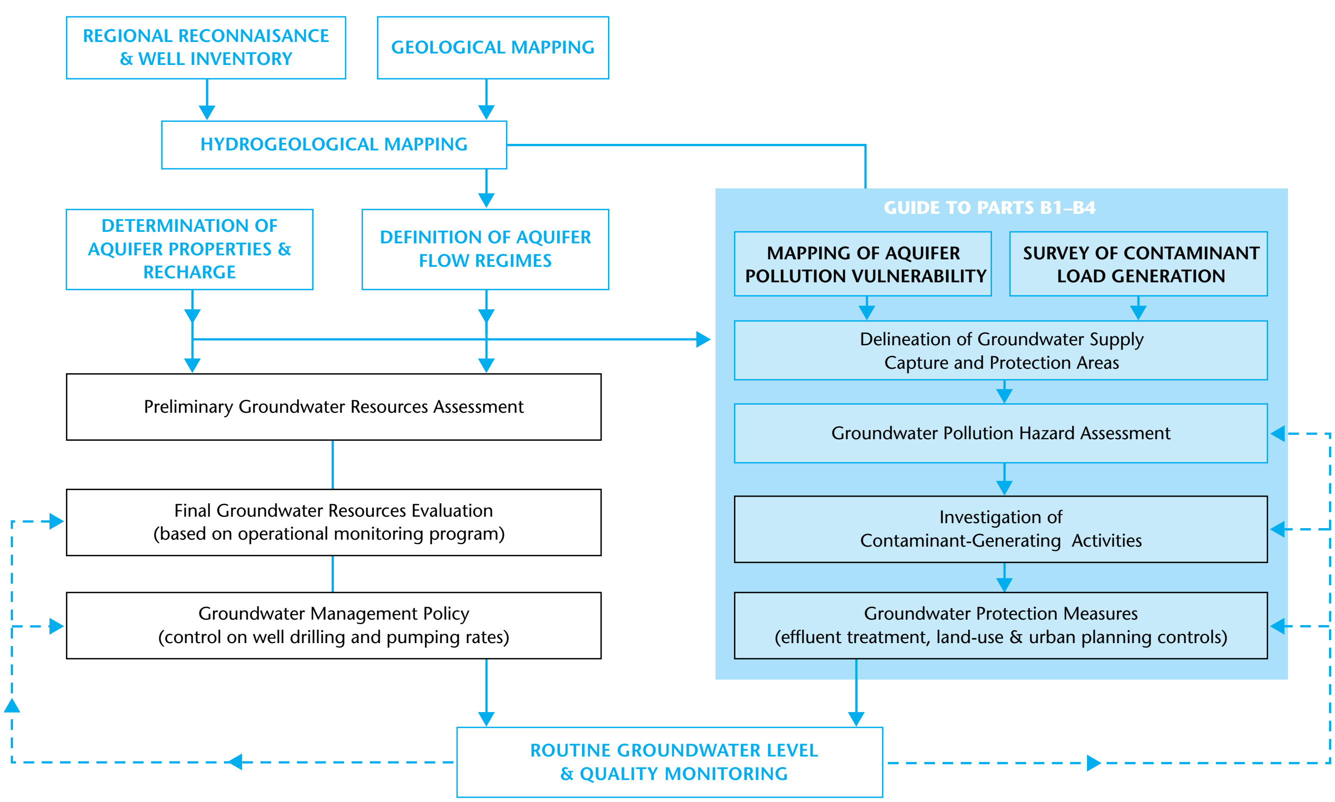
local government or municipal authority to take protective action under decree in the greater interest of the local population.

- The procedures for groundwater pollution hazard assessment presented also constitute an effective vehicle for initiating the involvement of relevant stakeholders (including water user interests and potential groundwater polluters).

9. What are the human and financial resource implications?

- The proposed assessment procedure will require the participation of at least two qualified professionals—a groundwater specialist/hydrogeologist (as team leader) and an environment engineer/scientist—normally supported by some auxiliary staff with a local office base and field transport.
- Although the methodology presented is relatively simple, it will be necessary for the professional staff involved to have a reasonable understanding of groundwater pollution. Moreover, skills will need to be developed (both on job and through consultation) in ranking some of the more subjective components of aquifer pollution vulnerability and subsurface contaminant load assessment.
- The boundaries of an assessment area (while recognizing the focus of particular interest) must

Figure A.7 Scope of *Guide* in context of overall scheme of groundwater resource management



be defined on a physical basis to include an entire aquifer or groundwater sub-catchment within an aquifer, so as always to include the probable recharge area of the system under consideration.

- The assessment procedure is highly complementary to other groundwater investigation, evaluation, and management actions (Figure A.7). It is designed to be undertaken relatively rapidly, and to utilize data that has already been collected for other purposes, or that can readily be collected at field level. Following the methodology presented, it should be possible for an appropriate team to complete a groundwater resource and supply pollution hazard assessment within 2–12 months, depending on the size and complexity of the area under consideration.

Part B: Technical Guide

Methodological Approaches to Groundwater Protection

A Technical Guide for professional groundwater specialists, environment engineers, and scientists, who are called upon to develop groundwater quality protection strategies for water service companies and water resource agencies, or are concerned with land-use planning, effluent discharge, and waste disposal control in environment agencies and municipal authorities.

Part B: Technical Guide

Methodological Approaches to Groundwater Protection

B1

Mapping Aquifer Pollution Vulnerability

The mapping of aquifer pollution vulnerability will normally be the first step in groundwater pollution hazard assessment and quality protection, when the interest is at municipal or provincial scale. This chapter discusses the evolution of the aquifer pollution vulnerability concept before recommending a methodological basis for vulnerability evaluation that can be used for mapping at that scale. The concept is also valid for vulnerability appraisal at more local levels within individual groundwater supply catchment areas.

1.1 Principles Underlying the Vulnerability Approach

Groundwater recharge mechanisms and the natural contaminant attenuation capacity of subsoil profiles vary widely with near-surface geological conditions. Thus, instead of applying universal controls over potentially polluting land uses and effluent discharges, it is more cost effective (and less prejudicial to economic development) to vary the type and level of control according to this attenuation capacity. This is the basic premise underlying the concept of aquifer pollution vulnerability and the need for vulnerability mapping.

In view of the complexity of factors governing pollutant transport into aquifers in any given situation, it might at first sight appear that:

- hydrogeological conditions are too complex to be encapsulated by mapped vulnerability zones
- it would be more logical to treat each polluting activity on individual merit and undertake an independent assessment of the pollution hazard it generates.

However this type of approach:

- is unlikely to achieve universal coverage and avoid inconsistent decisions
- requires large human resources and major financial investment for field investigations
- can present administrative problems where institutional responsibility is split.

1.2 Development of the Vulnerability Concept

In hydrogeology the term "vulnerability" began to be used intuitively from the 1970s in France (Albinet and Margat, 1970) and more widely in the 1980s (Haertle, 1983; Aller and others, 1987; Foster and Hirata, 1988). While the implication was of relative susceptibility of aquifers to anthropogenic pollution, initially the term was used without any attempt at formal definition.

The expression began to mean different things to different people. A useful and consistent definition would be to regard aquifer pollution vulnerability as those intrinsic characteristics of the strata separating the saturated aquifer from the land surface, which determine its sensitivity to being adversely affected by a surface-applied contaminant load (Foster,-1987). It would then be a function of:

- the accessibility of the saturated aquifer, in a hydraulic sense, to the penetration of pollutants
- the attenuation capacity of strata overlying the saturated zone resulting from the physiochemical retention or reaction of pollutants.

In the same way, groundwater pollution hazard would then be defined as the probability that groundwater in the uppermost part of an aquifer will become contaminated to an unacceptable level by activities on the immediately overlying land surface (Foster and Hirata, 1988; Adams and Foster, 1992).

Subsequently two major professional working groups reviewed and pronounced upon the applicability of the vulnerability concept and come out strongly in favor of its usefulness (NRC, 1993; IAH/Vrba and Zaporozec, 1994). It would have been desirable for them to have made a clearer statement on the use of the term, for example associating it specifically with the intrinsic characteristics of the strata (unsaturated zone or confining beds) separating the saturated aquifer from the land surface (Foster and Skinner, 1995). This would (most importantly) have related it directly with the potential impact of land-use decisions at the location concerned on the immediately underlying groundwater.

Some, however, considered that a factor representing the natural mobility and persistence of pollutants in the saturated zone be included in vulnerability. This, however, does not appear to view vulnerability mapping from the most useful perspective, namely that of providing a framework for planning and controlling activities at the land surface.

Need for an Absolute Integrated Vulnerability Index

1.3

Two fundamental questions that arise in relation to aquifer pollution vulnerability are whether it is possible:

- to present a single integrated vulnerability index, or be obliged to work with specific vulnerability to individual contaminants and to pollution scenarios
- to provide an absolute indicator of integrated pollution vulnerability, or be restricted to much less useful relative vulnerability indices.

Subsurface water flow and contaminant transport are intricate processes. In reality, the interaction between components of aquifer pollution vulnerability and subsurface contaminant load, which determine the groundwater pollution hazard, can be complex (Figure 1.1). In particular, the degree of contaminant attenuation can vary significantly with the type of pollutant and polluting process in any given situation. Thus a "general (integrated) vulnerability to a universal contaminant in a typical pollution scenario" has no strict validity in rigorous terms (Foster and Hirata, 1988).

Scientifically, it is more consistent to evaluate vulnerability to pollution by each pollutant, or failing this by each class of pollutant (nutrients, pathogens, microorganics, heavy metals, etc.) individually, or by each group of polluting activities (unsewered sanitation, agricultural cultivation, industrial effluent disposal, etc.) separately. For this reason (Andersen and Gosk, 1987) suggested that vulnerability mapping would be better carried out for individual contaminant groups in specific pollution scenarios. However, the implication would be an atlas of maps for any given area, which would be difficult to use in most applications, except perhaps the evaluation and control of diffuse agricultural pollution (Carter and others, 1987; Sokol and others, 1993; Loague, 1994).

Moreover, there will not normally be adequate technical data and/or sufficient human resources to achieve this ideal. In consequence, a less refined and more generalized system of aquifer vulnerability mapping is required. The way forward for most practical purposes is to produce an integrated vulnerability map, provided the terms being used are clearly defined and the limitations clearly spelled out (Foster and Hirata, 1988). Such health warnings have been elegantly expressed in the recent U.S. review (NRC, 1993) in the form of three laws of groundwater vulnerability:

- all groundwater is to some degree vulnerable to pollution
- uncertainty is inherent in all pollution vulnerability assessments
- in the more complex systems of vulnerability assessment, there is risk that the obvious may be obscured and the subtle indistinguishable.

An absolute index of aquifer pollution vulnerability is far more useful (than relative indications) for all practical applications in land-use planning and effluent discharge control. An absolute integrated index can be developed provided each class of vulnerability is clearly and consistently defined (Table 1.1). In this way it is possible to overcome most

Figure 1.1 Interactions between components of subsurface contaminant load and aquifer pollution vulnerability determining aquifer pollution hazard

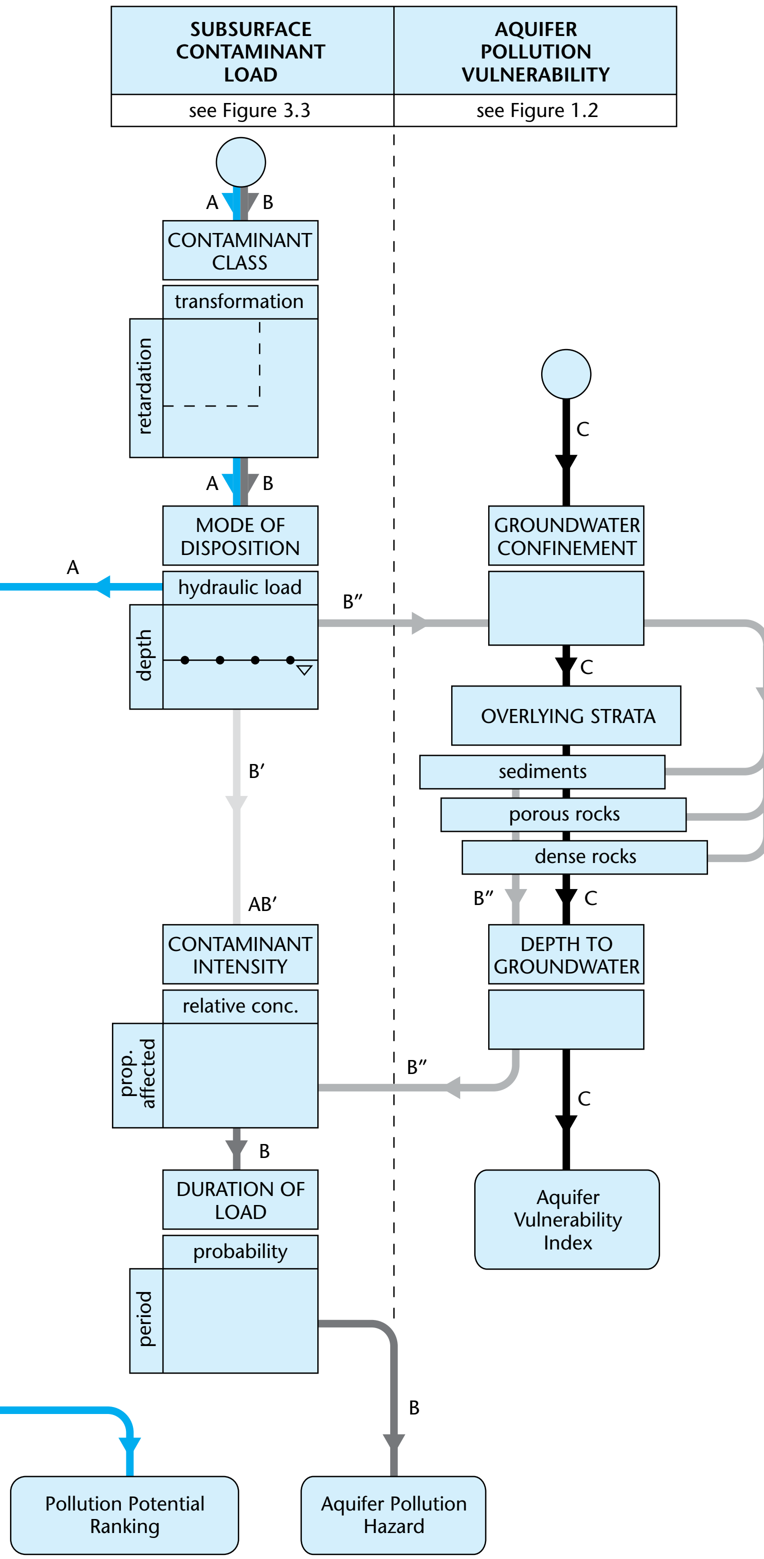


Table 1.1 Practical definition of classes of aquifer pollution vulnerability

VULNERABILITY CLASS	CORRESPONDING DEFINITION
Extreme	vulnerable to most water pollutants with rapid impact in many pollution scenarios
High	vulnerable to many pollutants (except those strongly absorbed or readily transformed) in many pollution scenarios
Moderate	vulnerable to some pollutants but only when continuously discharged or leached
Low	only vulnerable to conservative pollutants in the long term when continuously and widely discharged or leached
Negligible	confining beds present with no significant vertical groundwater flow (leakage)

(if not all) the common objections to the use of an absolute integrated vulnerability index as a framework for groundwater pollution hazard assessment and protection policy formulation.

1.4 Application of GOD Vulnerability Index

The GOD method of aquifer pollution vulnerability assessment has had wide trials in Latin America and the Caribbean during the 1990s (Table 1.2), and because of its simplicity of concept and application, it is the preferred method described in this Guide.
Two basic factors are considered to determine aquifer pollution vulnerability:

- the level of hydraulic inaccessibility of the saturated zone of the aquifer
- the contaminant attenuation capacity of the strata overlying the saturated aquifer;

however they are not directly measurable and depend in turn on combinations of other parameters (Table 1.3). Since data relating to many of these parameters are not generally available, simplification of the list is unavoidable if a practical scheme of aquifer pollution vulnerability mapping is to be developed.

Based on such considerations, the GOD vulnerability index (Foster, 1987; Foster and Hirata, 1988) characterizes aquifer pollution vulnerability on the basis of the following (generally available or readily determined) parameters:

- Groundwater hydraulic confinement, in the aquifer under consideration.
- Overlying strata (vadose zone or confining beds), in terms of lithological character and degree of consolidation that determine their contaminant attenuation capacity
- Depth to groundwater table, or to groundwater strike in confined aquifers.

Table 1.2 Some applications of aquifer pollution vulnerability mapping and groundwater pollution hazard assessment in the Latin America–Caribbean Region*

Area of of Study	Authors	Date	Working Map Scale	Vulnerability Method Adopted	Contaminant Inventory	Source Capture Zones Defined	GIS Used
Barbados	Chilton and others	1990	1:100,000	GOD	✔	✔	
São Paulo, Brazil	Hirata and others	1990	1:500,000	GOD	✔		✔
Río Cuarto, Argentina	Blarasín and others	1993, 1999	1:50,000	GOD	✔		
Managua, Nicaragua	Scharp and others	1994, 1997	1:100,000	DRASTIC/GOD	✔	✔	✔
Leon, Mexico	Stuart and Milne	1997	1:50,000	GOD	✔	✔	
Caçapava, Brazil	Martin and others	1998	1:100,000	GOD	✔	✔	✔
Esperanza, Argentina	Paris and others	1998, 1999	1:50,000	GOD	✔	✔	
Cauca Valley, Colombia	Paez and others	1999	1:200,000	GOD(S)			✔

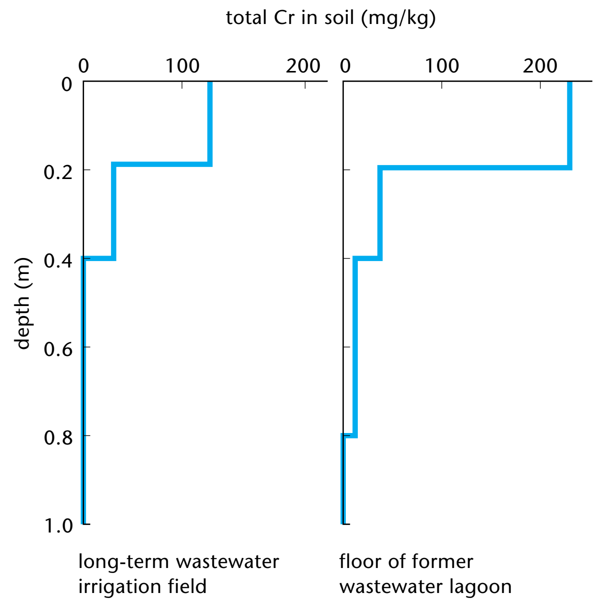
*These are the sources of information for all the text boxes.

Box 1.1
Vulnerability of semi-confined aquifers—field data from León, Mexico

It is important to note that a semi-confined aquifer of low pollution vulnerability can be seriously impacted in the long run by persistent contaminants (such as chloride, nitrate, and certain synthetic organic compounds), if they are continuously discharged on the overlying ground surface. This possibility must always be taken into account when assessing the pollution hazard to waterwells abstracting from such aquifers.

- León (Guanajuato) is one of the fastest-growing cities in Mexico and one of the most important leather-manufacturing and shoe-making centers in Latin America. The city is located in an arid upland tectonic valley filled by a mixture of alluvial, volcanic, and lacustrine deposits, which form a thick complex multi-aquifer system.
- A substantial proportion of the municipal water supply is derived from downstream wellfields, which tap a semi-confined aquifer from below a 100-meter depth. One of the wellfields is situated where municipal wastewater has been used over various decades for agricultural irrigation. The inefficient irrigation characteristic of wastewater reuse results in a substantial (and continuous) recharge of the local groundwater system. Thus groundwater levels have here remained within 10 meters of the land surface, despite the fact that in neighboring areas they have been in steady long-term decline at rates of 1–3 meters per year (m/a).
- The wastewater historically included an important component of industrial effluent with very high dissolved chromium, organic carbon and overall salinity. Detailed field investigations in the mid-1990s by the Comision Nacional del Agua-Gerencia de Aguas Subterraneas and the Servicio de Agua Potable de Leon have shown that most elements of the contaminant load (including pathogenic microbes and heavy metals) are rapidly attenuated in the subsoil profile (Figure A). Very little reaches the semi-confined aquifer (Stuart and Milne, 1997), whose pollution vulnerability under the GOD system would classify in the low range.
- However, persistent contaminants—notably salinity as indicated by Cl concentrations (Figure B)—do penetrate into the semi-confined aquifer and are threatening the quality and security of municipal water supplies in this area (Stuart and Milne, 1997).

(A) Attenuation of chromium in soils of wastewater irrigation area



(B) Variation of groundwater quality with depth beneath wastewater irrigation

SOURCE OF SAMPLE	TYPICAL SHALLOW WELL	PUBLIC SUPPLY BOREHOLES
intake depth	<30 m	200–300 m
EC (µS/cm)	3400	1000
Cl (mg/l)	599	203
HCO_3 (mg/l)	751	239
NO_3 (mg/l)	13.5	6.0
Na (mg/l)	227	44

Table 1.3 Hydrogeological factors controlling aquifer pollution vulnerability

COMPONENT OF VULNERABILITY	HYDROGEOLOGICAL DATA ideally required	normally available
Hydraulic Inaccessibility	degree of aquifer confinement	type of groundwater confinement
	depth to groundwater table or groundwater strike	depth to groundwater table or top of confined aquifer
	unsaturated zone moisture content vertical hydraulic conductivity of strata in vadose zone or confining beds	
Attenuation Capacity	grain and fissure size distribution of strata in vadose zone or confining beds	grade of consolidation/fissuring these strata
	mineralogy of strata in vadose zone or confining beds	lithological character of these strata

Further consideration reveals that these parameters embrace, if only in a qualitative sense, the majority of those in the original list (Table 1.3).

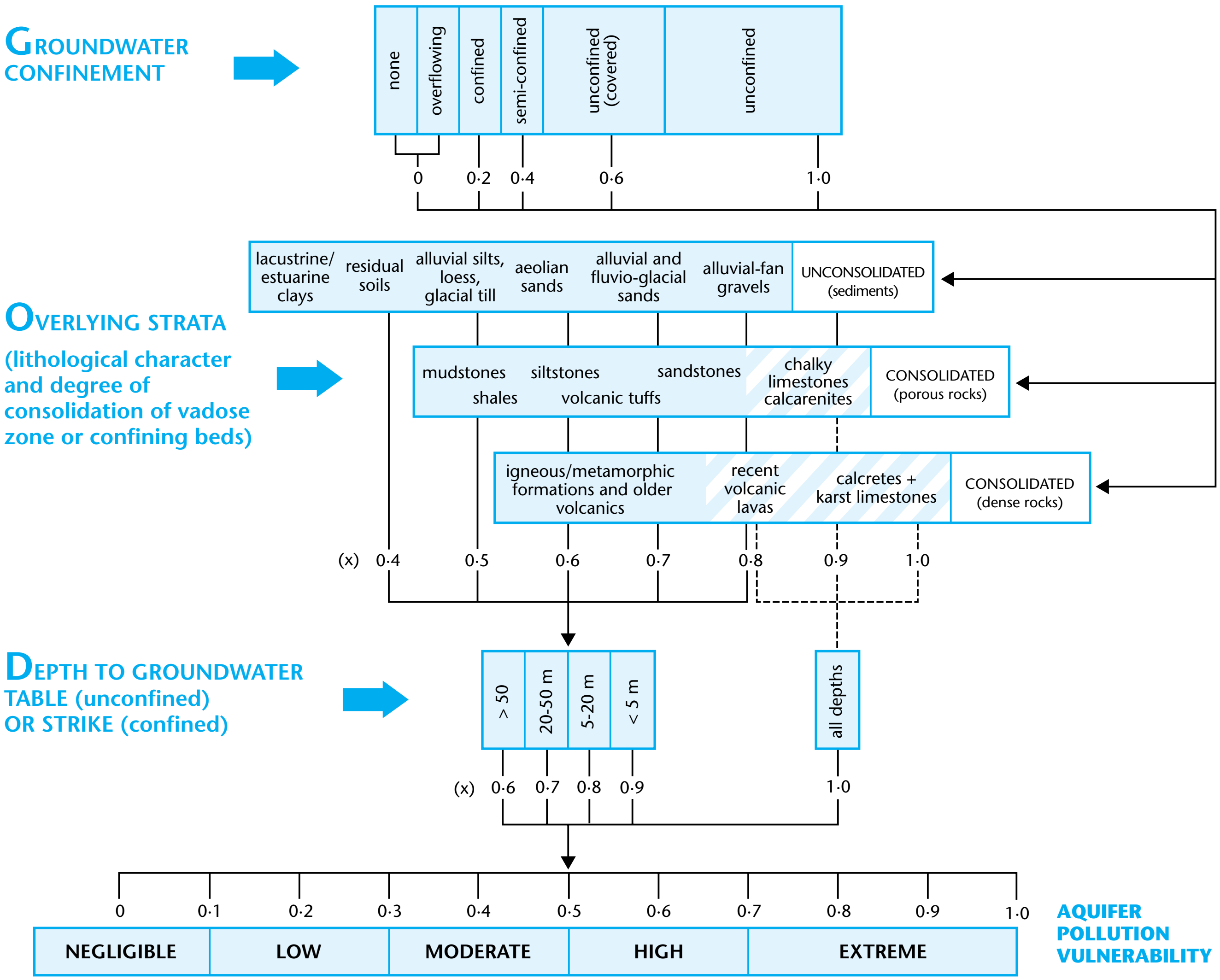
The empirical methodology proposed for the estimation of aquifer pollution vulnerability (Foster and Hirata, 1988) involved a number of discrete stages:

- first, identification of the type of groundwater confinement, with consequent indexing of this parameter on scale-0–1
- second, specification of the strata overlying the aquifer saturated zone in terms of (a) grade of consolidation (and thus likely presence or absence of fissure permeability) and (b) type of lithology (and thus indirectly dynamic—effective—porosity, matrix permeability, and unsaturated zone moisture content or specific retention); this leads to a second score on a scale 0.4–1.0
- third, estimation of the depth to groundwater table (of unconfined aquifers) or depth of first major groundwater strike (for confined aquifers), with consequent ranking on the scale 0.6–1.0.

The final integrated aquifer vulnerability index is the product of component indices for these parameters (Figure 1.2). It should be noted that this figure has been modified slightly from the original version (Foster and Hirata, 1988) in light of experiences in its application during the 1990s. The modifications include:

- somewhat reduced weighting to the "depth to groundwater" factor
- some simplification of the geological descriptors as regards "potentially fractured rocks of intermediate intrinsic vulnerability"
- clarification of the "groundwater confinement" factor as regards semi-confined aquifers.

Figure 1.2 GOD system for evaluation of aquifer pollution vulnerability



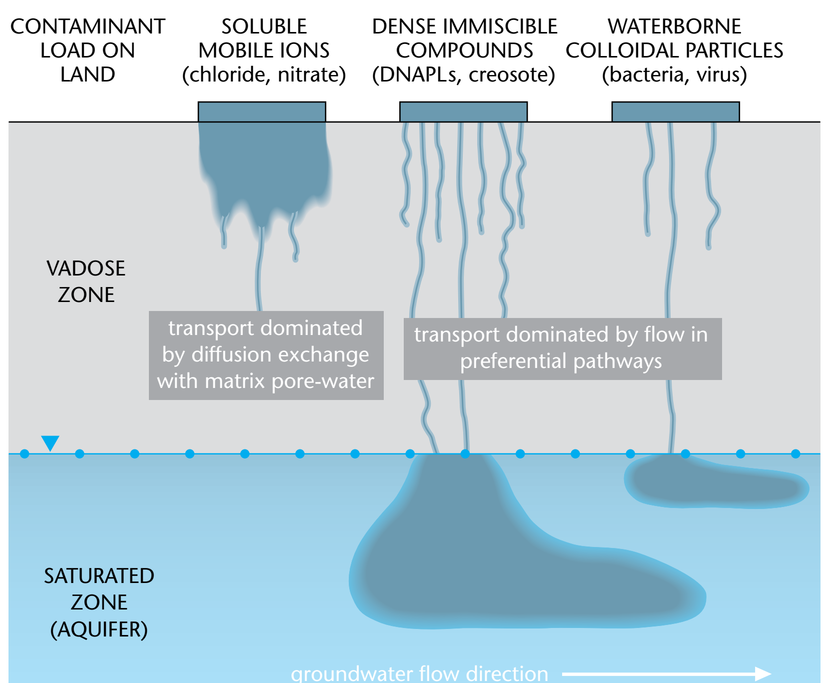
It should also be noted that, where a variable sequence of deposits is present, the predominant or limiting lithology should be selected for the purpose of specification of the overlying strata.

In the GOD scheme, a descriptive subdivision of geological deposits (involving grain-size and mineral characteristics) could have been used and might appear easier to apply. However, a genetic classification better reflects factors important in the pollution vulnerability context (such as depositional structure), and thus a hybrid system (compatible with those used for many geological maps) is adopted. Almost all of the sediments in the classification (Figure 1.2) are transported geological deposits. However, two other types of deposits are retained because of their widespread distribution—deep residual soils (such as the laterites of the tropical belt) and desert calcretes (an in-situ deposit).

In the context of the classification of overlying strata, there was concern that too much consideration might inadvertently be placed on dynamic porosity (and thus merely on recharge time lag rather than contaminant attenuation). Vulnerability would then (incorrectly) become more a measure of when (as opposed to if and which) pollutants reach the aquifer. Thus greatest emphasis was put upon the likelihood of well-developed fracturing being present, since this may promote preferential flow even in porous strata such as some sandstones and limestones (Figure 1.3). The possibility of such flow is considered the most critical factor increasing vulnerability and reducing contaminant attenuation, given that hydraulic (fluid) surcharging is associated with many pollution scenarios.

The original GOD vulnerability scheme did not include explicit consideration of soils in an agricultural sense. However, most of the processes causing pollutant attenuation and/or elimination in the subsurface occur at much higher rates in the biologically active soil zone, as a result of its higher organic matter, larger clay mineral content and very much larger bacterial populations. A possible modification to the method (GODS) incorporates a soil leaching susceptibility index (based on a soil classification according to soil texture and organic content), as a fourth step capable of reducing overall ranking in some areas of high hydrogeological vulnerability. Within urban areas the soil is often removed during construction or the subsurface pollutant load is applied below its base in excavations (such as pits, trenches, or lagoons), thus the soil zone should be assumed absent and the uncorrected hydrogeological vulnerability used.

Figure 1.3 Development and consequences of preferential flow in the vadose zone



Comparison with Other Methodologies

1.5

A number of other schemes of aquifer pollution vulnerability assessment have been presented in the literature, and these can be classified into three main groups according to the approach adopted (Vrba and Zaporozec, 1995):

- Hydrogeological Settings: these base vulnerability assessment in qualitative terms on the general characteristics of the setting using thematic maps (eg. Albinet and Margat, 1970)
- Analogue Models: these utilize mathematical expressions for key parameters (such as average vadose zone transit time) as an indicator of vulnerability index (EC/Fried approach in Monkhouse, 1983)
- Parametric Systems: these use selected parameters as indicative of vulnerability and assign their range of values and interactions to generate some form of relative or absolute vulnerability index (examples of this approach include Haertle, 1983 and DRASTIC of Aller and others, 1987, in addition to the GOD methology described in this Guide). A further method of note in this category is EPIK, which is specifically designed for karst limestone aquifers only and usefully discussed by Doerfliger and Zwahlen, 1998; Gogu and Dassargues, 2000; Daly and others, 2001.

Among these the best known is the DRASTIC methodology. It attempts to quantify relative vulnerability by the summation of weighted indices for seven hydrogeological variables (Table 1.4). The weighting for each variable is given in parentheses, but changes (especially for parameters S and T) if vulnerability to diffuse agricultural pollution alone is under consideration.

The method has been the subject of various evaluations (Holden and others, 1992; Bates and others, 1993; Kalinski and others, 1994; Rosen, 1994). All of these evaluations revealed both various benefits and numerous shortcomings of this methodology. On balance, it is considered that the method tends to generate a vulnerability index whose significance is rather obscure. This is a consequence of the interaction of too many weighted parameters, some of which are not independent but quite strongly correlated. The fact that similar indices can be obtained by a very different combination of circumstances may lead to dangers in decision making.

Table 1.4 Factors and weightings in the DRASTIC pollution vulnerability index

- Depth to groundwater (X5)
- Natural Recharge rates (X4)
- Aquifer media (X3)
- Soil media (X2)
- Topographic aspect (X1)
- Impact (effect) of vadose zone (X5)
- Hydraulic Conductivity (X3)

Box 1.2

Aquifer pollution vulnerability mapping incorporating a soil-cover factor in the Cauca Valley, Colombia

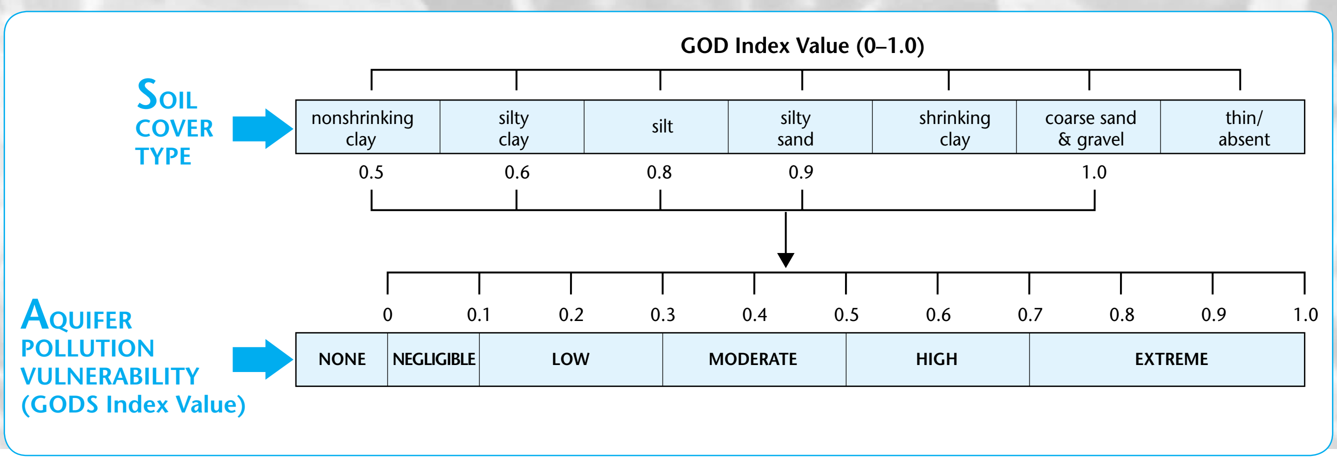
Some Latin American workers have proposed a modification to the GOD method of aquifer pollution vulnerability estimation, which adds a factor in respect of the attenuation capacity of the soil cover, based on texture alone. In general terms it is considered valid to include a "soil factor," although not in areas where there is risk that the soil profile has been removed or disturbed and not in cases where the contaminant load is applied below the base of the soil. Moreover, if a soil factor is to be included it is preferable to base it upon soil thickness, together with those properties which most directly influence in-situ denitrification and pesticide attenuation (namely the soil texture and organic content).

- The Cauca Valley has the largest groundwater storage resources of Colombia, and its aquifers currently support an abstraction of around 1000 Mm^3/a, which is of fundamental importance to the valley's economic development and provides the municipal water supply for various towns including Palmira, Buga, and parts of Cali. The valley is a major tectonic feature with a large thickness of mixed valley-fill deposits in which alluvial fan and lacustrine deposits predominate.

- With the aim of providing a tool for land-use planning to protect these resources, the pollution vulnerability of the aquifers was mapped by the local water resource agency (the Corporación del Valle de Cauca) using the GOD method. A modification was introduced (as first proposed by the Pontificia Universidad de Chile-Dpto de Ingenieria Hidraulica y Ambiental) incorporating an S factor in respect of the contaminant attenuation capacity of the soil cover. The modified methodology (known as GODS) involves assigning values of S according to the textural characteristics of the soil, which range from very fine (predominantly clayey) to very coarse (gravelly), in areas where this is more than 0.5m thick.

- A map of the values of this soil-cover factor was produced, which was then overlaid on the GOD aquifer vulnerability index map. In areas where the soil cover was well preserved and of substantial thickness, the value of the GOD index was correspondingly reduced (Paez, 1999).

- The Environment Agency of England & Wales also include a soil factor in their aquifer vulnerability mapping. This is based on a set of soil properties determining leaching susceptibility, but its effect is limited to potentially reducing the mapped vulnerability level in rural areas, and it is not considered operative in urban areas—where soil profile disturbance due to engineering construction is widespread (Foster, 1997).



More specifically it should also be noted that:

- the method underestimates the vulnerability of fractured (compared to unconsolidated) aquifers
- including a parameter reflecting contaminant mobility in the saturated zone is an unnecessary complication (for reasons stated earlier).

Limitations of Vulnerability Mapping 1.6

A number of hydrogeological conditions present problems for aquifer pollution vulnerability assessment and mapping:

- the occurrence of (permanent or intermittent) losing streams, because of uncertainties in evaluating the hydrological condition, in defining the quality of the watercourse and in appraising streambed attenuation capacity (it is, however, essential to indicate potentially influent sections of streams crossing unconfined aquifers)
- excessive aquifer exploitation for water supply purposes, which can vary the depth to groundwater table and even the degree of aquifer confinement, but given the scheme of indexation proposed, such effects will only occasionally be significant
- over-consolidated (and therefore potentially fractured) clays, for which there are usually significant uncertainties about the magnitude of any preferential flow component.

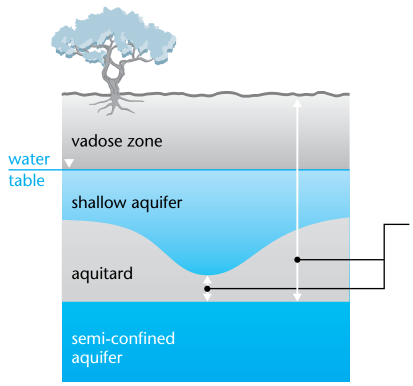
Aquifer vulnerability maps are only suitable for assessing the groundwater pollution hazard associated with those contaminant discharges that occur at the land surface and in the aqueous phase. Strictly speaking they should not be used for assessing the hazard from:

- contaminants discharged deeper in the subsurface (as may be the case in leakage of large underground storage tanks, solid-waste landfill leachate, effluent discharges to quarries, and mine shafts, etc.)
- spillages of heavy immiscible synthetic organic pollutants (DNAPLs).

Both are likely to result in high groundwater pollution hazard regardless of aquifer vulnerability. The only consideration in such circumstances will be the intensity and probable duration of the load. The technical validity of the aquifer pollution vulnerability index and map can be maintained, if it is made clear that these types of contaminant load are excluded from consideration by the proposed methodology and that such practices need to be specifically controlled irrespective of field conditions.

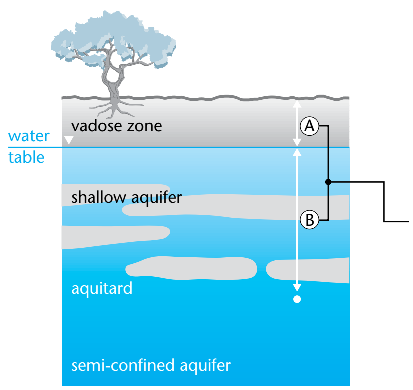
Another condition that needs a special procedure is the existence of naturally poor-quality (normally saline) groundwater at shallow depth. This requires specific mapping since such aquifers will not generally merit special protection, even in cases of high anthropogenic pollution vulnerability.

Figure 1.4 Interpretation of the pollution vulnerability of semi-confined aquifers



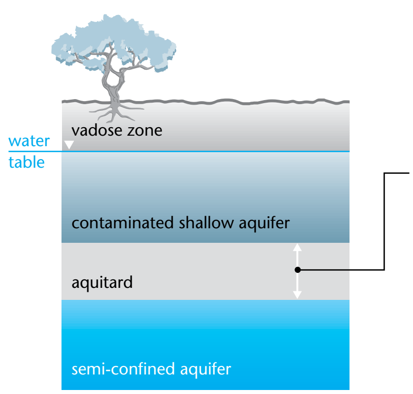
Problem: using the GOD method, the **O factor** represents the lithology of confining beds or unsaturated zones, but for semi-confined aquifers this is difficult to determine

Solution: consider the thinnest part of the aquitard and calculate the **O factor** as a weighted value of different materials (vadose zone, shallow aquifer, and aquitard)



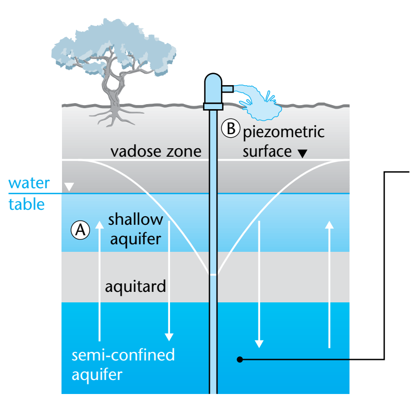
Problem: using the GOD method, the **D factor** is the distance between the land surface and the water table or water strike, but for a semi-confined aquifer what is the correct value?

Solution: use the depth to the aquifer (A+B)



Problem: poor quality shallow aquifer covering the semi-confined aquifer that requires protection

Solution: consider the shallow aquifer as a potential contaminant source and thus use the characteristics of the aquitard only for the **O** and **D** factors



Problem: hydraulic inversion caused by groundwater extraction from deep aquifer

Solution: use **G factor** appropriate to new hydraulic condition and treat deep aquifers as now semi-confined or even covered

Procedural Issues in Vulnerability Mapping

1.7

The generation of the map of GOD aquifer vulnerability indices follows the procedures indicated in Figure 1.5. Such a process can be carried out manually for a series of points on a grid basis and contoured, but is increasingly generated by GIS (geographical information system) technology.

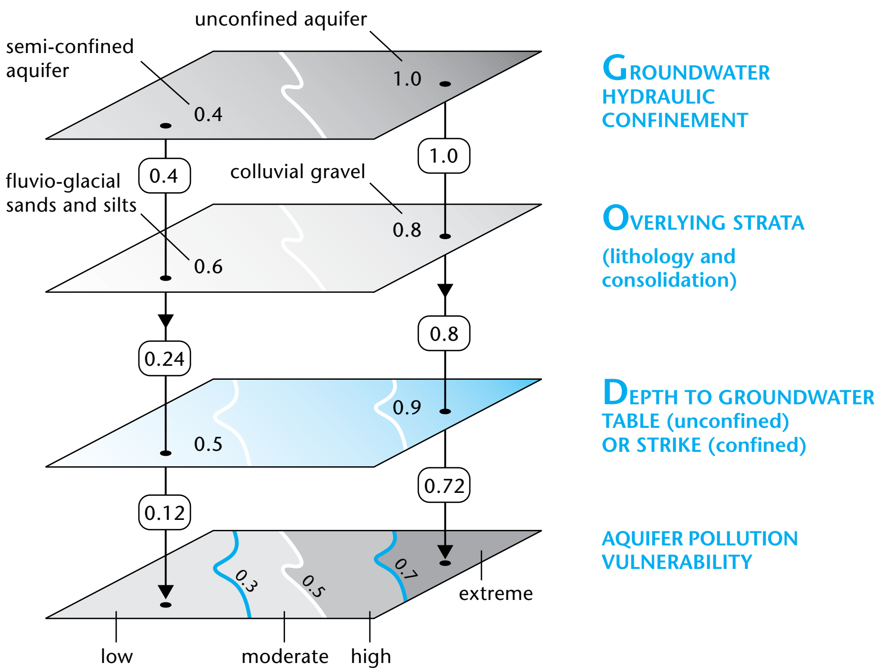
In the majority of instances, hydrogeological maps and/or groundwater resource reports will be available, and generally these will contain adequate basic data to undertake the evaluation procedure proposed. However, it will often be necessary to supplement this information by the direct study of geological maps and waterwell drilling records, and sometimes by limited field inspection.

(A) Approach to Layered Aquifers

One of the most frequent difficulties encountered in aquifer pollution vulnerability mapping is the presence of layering of strata of widely different water-transmitting properties. Stratification is a fundamental characteristic of both sedimentary and volcanic geological formations, and such formations include almost all major, and many minor, aquifers. Problems may result when the layering occurs both:

- above the regional groundwater table, giving rise to perched aquifers or covered unconfined aquifers (where weighted average or limiting values of the relevant properties need to be considered), and

Figure 1.5 Generation of aquifer pollution vulnerability map using the GOD system



- below the regional groundwater table, causing semi-confinement of aquifers at depth (for which a consistent decision needs to be clearly made and stated on which aquifer is represented by vulnerability mapping, and the attenuation capacity of the overlying strata assessed accordingly).

The approach to classification detailed in Figure 1.4 should then be followed for vulnerability estimation, and a record made (by suitable ornament) where an overlying (more vulnerable) local aquifer is also present.

(B) Necessary Level of Simplification

It must be stressed that aquifer pollution vulnerability maps are designed to provide a general framework within which to base groundwater protection policy. The two, however, are distinct in both concept and function. The former should represent a simplified (but factual) representation of the best available scientific data on the hydrogeological environment, no more or no less. This general framework is not intended to eliminate the necessity to consider in detail the design of actual potentially polluting activities before reaching policy decisions.

Aquifer vulnerability maps are aimed only at giving a first general indication of the potential groundwater pollution hazard to allow regulators, planners, and developers to make better informed judgements on proposed new developments and on priorities in groundwater pollution control and quality monitoring. They are based on the best available information at the time of production and will require periodic updating.

In concept and in practice they involve much simplification of naturally complex geological variations and hydrogeological processes. Site-specific questions need to be answered by site-specific investigations, but the same philosophical and methodological approach to the assessment of groundwater pollution hazard is normally possible.

The data required for the assessment of aquifer pollution vulnerability—and for that matter inventories of subsurface contaminant loads—should (wherever possible) be developed on a suitable GIS platform, to facilitate interaction, update, and presentation. Separate colors can be used for major lithological divisions of the strata overlying the saturated zone, with different densities of color for each subdivision of depth to groundwater.

B2

Delineation of Groundwater Supply Protection Areas

Groundwater supply protection areas (called wellhead protection zones in the United States) should be delineated to provide special vigilance against pollution for water sources destined for public (mains) water supply. Consideration must also be given to sources developed for other potentially sensitive uses, and especially of bottled natural mineral waters, which do not receive any form of disinfection.

2.1 Basis for Definition of Perimeters of Areas

The concept of groundwater supply protection is long established, being part of legal codes in some European countries for many decades. However, increasing hydrogeological knowledge and changes in the nature of threats to groundwater quality mean that the concept has had to evolve significantly and requires consolidation (US-EPA, 1994; NRA, 1995; EA, 1998).

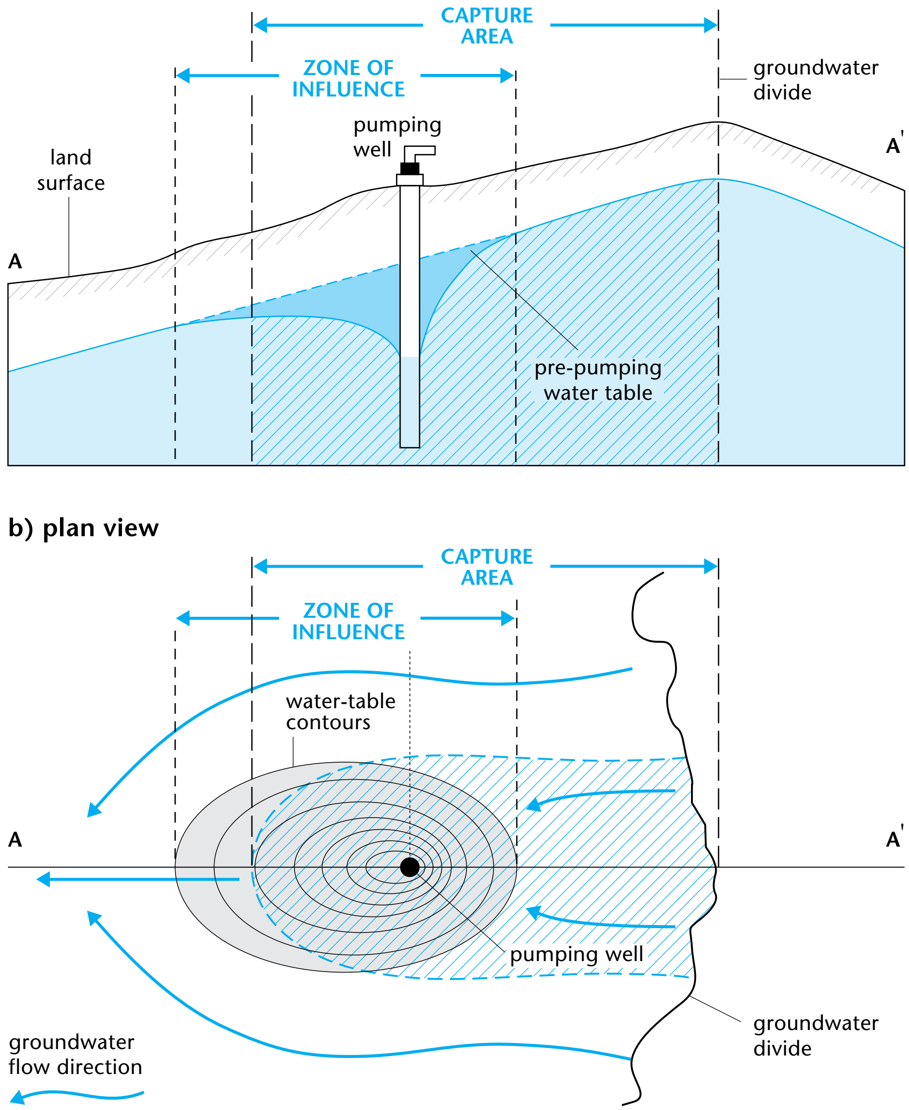
A key factor influencing the hazard posed by a land-use activity to a groundwater supply (well, borehole, or spring) is its proximity. More specifically, the pollution threat depends on:

- whether the activity is located within the (subsurface) capture area of that supply (Figure 2.1)
- the horizontal groundwater flow time in the saturated aquifer from the location of the activity to the point of abstraction of the supply.

Figure 2.1 Distinction between area of capture and zone of influence of a production waterwell

a) vertical profile

b) plan view



Supply protection areas (SPAs)—also known as source protection zones (SPZs)—have to defend against:

- contaminants that decay with time, where subsurface residence time is the best measure of protection
- nondegradable contaminants, where flowpath-dependent dilution must be provided.

Both are necessary for comprehensive protection. Contaminant dilution resulting from the advection and dispersion mechanisms associated with groundwater flow is usually the dominant attenuation process, but degradation (breakdown) is also likely to occur for some contaminants (and various other processes such as adsorption and precipitation for others).

In order to eliminate completely the risk of unacceptable pollution of a supply source, all potentially polluting activities would have to be prohibited (or fully controlled) within its entire recharge capture area. This will often be untenable or uneconomic, however, due to socio-economic pressure for development. Thus, some division of the recharge capture zone is required, so that the most stringent land-use restrictions will only be applied in areas closer to the source.

This subdivision could be based on a variety of criteria (including: horizontal distance, horizontal flow time, proportion of recharge area, saturated zone dilution, and/or attenuation capacity), but for general application it is considered that a combination of (horizontal) flow time and flow distance criteria are the most appropriate. Special protection of a proportion of the recharge capture area might (under certain circumstances) be considered the preferred solution to alleviate diffuse agricultural pollution, but even here the question arises of which part it is best to protect.

A series of generally concentric land-surface zones around the groundwater source can be defined, through knowledge of (and assumptions about) local hydrogeological conditions and the characteristics of the groundwater supply source itself. The three most important of these zones (Figure 2.2) are described below (Adams and Foster, 1992; Foster and Skinner, 1995). In the interests of supply protection, the zones will need to be subjected to increasing levels of control over land-use activities, which will tend to vary with local conditions and needs.

(A) Total Source Capture Area

The outermost protection zone that can be defined for an individual source is its recharge capture (or catchment) area. This is the perimeter within which all aquifer recharge (whether derived from precipitation or surface watercourses) will be captured in the water supply under consideration. This area should not be confused with the area of hydraulic interference caused by a pumping borehole, which is larger on the down-gradient side (Figure 2.1). Recharge capture areas are significant not only for quality protection but also in resource management terms, and in situations of intensive groundwater exploitation they might also be used as areas of resource conservation (or reserve) for potable supply.

The total capture zone is determined in area by water balance considerations and in geometry by groundwater flowpaths. It is the zone providing the protected long-term yield. Thus, if the groundwater flow system is assumed (as is normally the case) to be in steady-state, its area will be determined by reference to the long-term average groundwater recharge rate. However, it should be recognized that in extended drought (when groundwater recharge is lower than average), the actual capture area will be larger than that protected. Moreover, in areas where the aquifer is confined beneath impermeable strata, the capture area will be located distant from the actual site of groundwater abstraction (Figure 2.2b).

The protected yield is usually taken as the authorized (licensed) annual abstraction, but may be less than this where the licensed quantity is in practice:

- unobtainable, since it exceeds the hydraulic capacity of the borehole installation
- unsustainable, since it exceeds the available groundwater resource
- unreasonable, because it greatly exceeds actual abstraction.

In such situations the protected yield is better based on recent abstraction rates, together with any reasonably forecast increase.

(B) Microbiological Protection Area

Preventing ingestion of groundwater contaminated with pathogenic bacteria, viruses, and parasites is of paramount importance. These pathogens enter shallow aquifers from some septic tanks soakaways, latrines, contaminated drainage or surface watercourses, and various other routes. Inadequately constructed wells are particularly prone to this type of contamination. However, in all but the most vulnerable formations, contamination via the aquifer route is prevented by the natural attenuation capacity of the vadose zone or the semi-confining beds.

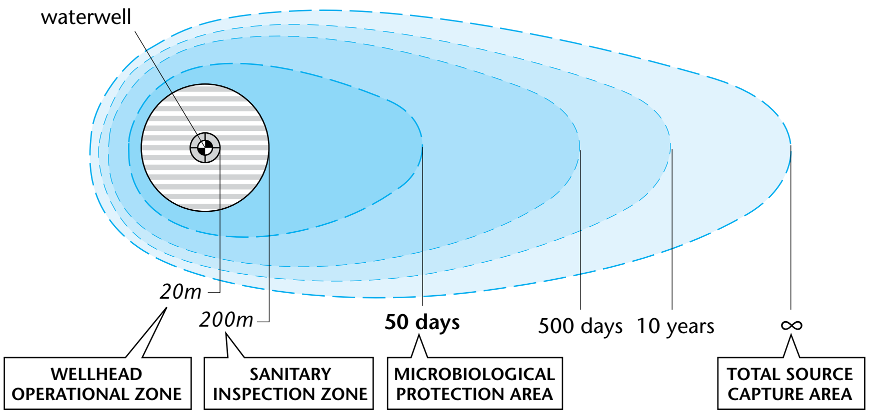
An inner protection zone based on the distance equivalent to a specified average horizontal flow time in the saturated aquifer has been widely adopted to protect against activities potentially discharging pathogenic viruses, bacteria, and parasites (Foster and Skinner, 1995), such as (for example) the spreading of wastewater and slurries on farmland. The actual flow time selected in different countries and at various times in the past, however, has varied significantly (from 10 to 400 days).

Published data (Lewis and others, 1982) suggests that the horizontal travel distance of pathogens in the saturated zone is governed principally by groundwater flow velocity. In all reported contamination incidents resulting in waterborne-disease outbreaks, the horizontal separation between the groundwater supply and the proven source of pathogenic pollution was (at maximum) the distance travelled by groundwater in 20 days in the corresponding aquifer flow regime. This was despite the fact that hardy pathogens are known to be capable of surviving in the subsurface for 400 days or more. Thus the 50-day isochron was confirmed a reasonable basis with which to define the zone (Figure-2.2), and this conforms with existing practice in many countries. This protection perimeter is perhaps the most important of all in terms of public health significance, and since it is usually small in size, implementation and enforcement are more readily achieved.

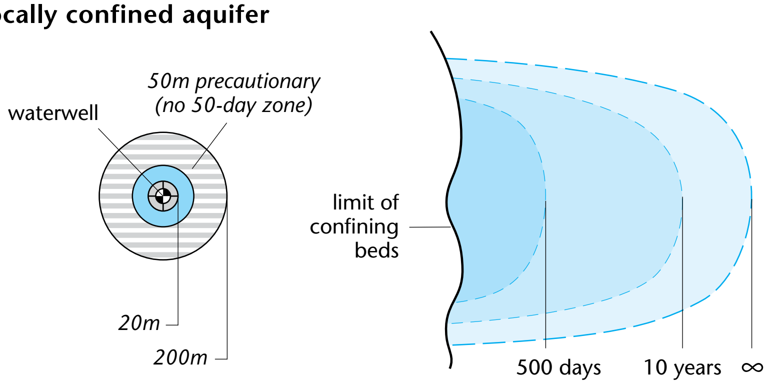
Experience has shown that in fissure-flow aquifers (which are often very heterogeneous in hydraulic properties), it is prudent to establish a limiting criterion of 50-m radius. Moreover, even if aquifers are covered or confined beneath thick low permeability strata, a 50-meter-radius zone is also recommended as a precautionary measure (Figure-2.2b), in recognition

Figure 2.2 Idealized scheme of groundwater capture areas and transit-time perimeters around a waterwell and springhead

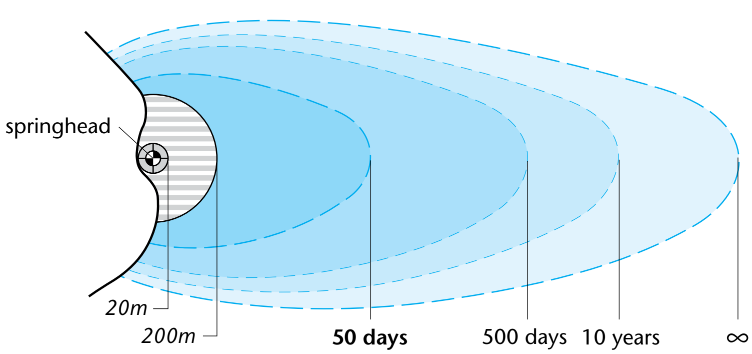
a) unconfined aquifer



b) locally confined aquifer



c) unconfined spring source



of the uncertainties of vertical flow and to protect against subsurface engineering construction, which could compromise source protection.

(C) Wellhead Operational Zone

The innermost protection perimeter is that of the wellhead operational zone, which comprises a small area of land around the supply source itself. It is highly preferable for this area to be under ownership and control of the groundwater abstractor. In this zone no activities should be permitted that are not related to water abstraction itself, and even these activities need to be carefully assessed and controlled (Figure 2.3) to avoid the possibility of pollutants reaching the source either directly or via adjacent disturbed ground. All parts of the zone used for well maintenance activities should have a concrete floor to prevent infiltration of oils and chemicals used in pump maintenance. Fencing is also standard practice to prevent invasion by animals and vandalism.

Specification of the dimension of this area is necessarily rather arbitrary and dependent to some degree on the nature of local geological formations, but a radius of at least 20-meters is highly desirable (Figure 2.2a). Detailed inspections of sanitary integrity, however, should be conducted over a larger area of 200 meters or more radius.

(D) Further Subdivision

It may be found useful to subdivide the total source capture area further, to allow gradational land-use controls beyond the microbiological protection zone. This can be done on the basis of a horizontal flow isochron of 500 days, for example (Figure 2.2a), to provide attenuation of slowly degrading contaminants. The selection of the time-of-travel is somewhat arbitrary. In reality such a perimeter is most significant in terms of providing time for remedial action to control the spread of persistent pollutants (at least in cases where a polluting incident is immediately recognized and notified) and is thus sometimes called the source inner-defensive zone.

Furthermore, a horizontal flow isochron of 10 years or more (Figure 2.2a) is sometimes substituted for the perimeter of the total capture area in high-storage aquifer systems with complex boundary conditions and/or abstraction regimes, where the former will be of less complex shape and subject to less scientific uncertainty.

2.2 Factors Controlling Shape of Zones

Most protection zone delineation has to assume that steady-state groundwater flow conditions effectively exist. On this basis the factors controlling the actual shape of the various zones to be delineated are summarized in Table 2.1.

Figure 2.3 Actual examples of wellhead completion for major public water supply boreholes

a) well-designed, drained, and maintained wellhead operational zone in rural wooded area

b) inadequately sized and protected wellhead operational zone threatened by agricultural irrigation with urban wastewater

Box 2.1
Operation of a long-standing groundwater source protection zone policy in Barbados

This case study reveals the benefits of early introduction of groundwater supply protection areas, even in situations where the nature of the aquifer flow regime and the pollution hazards are not yet completely understood. Supplementary actions can always be taken to subsequently reinforce existing provisions.

- The Caribbean island of Barbados is very heavily dependent upon groundwater for its public water supply, abstracting some 115 Ml/d from 17 production wells in a highly permeable karstic limestone aquifer of extreme pollution vulnerability.

- The potential impact of urban development and the great strategic importance of groundwater supplies led the Barbados government to establish special protection areas around all of its public-supply wells about 30 years ago. The perimeters of these protection areas are defined on the basis of average groundwater travel times to the wells, and the range of restrictions imposed is summarized in the table below. These for the most part have been successful in conserving water supply quality.

- At the time of introducing the policy, the main hazards to groundwater was perceived to be the spread of urbanization with in-situ sanitation around the capital, Bridgetown, and leakage from commercial and domestic oil storage installations.

- However, additional threats have subsequently emerged (Chilton and others, 1990) such as:
  - the replacement of traditional extensive sugar-cane cultivation with much more intensive horticultural cropping involving much higher fertilizer and pesticide applications
  - illegal disposal of industrial solid waste disposal by fly tipping in abandoned small limestone quarries and effluent disposal down disused wells.

Measures have now been introduced to control and to monitor such activities.

Principal features of development control zones

Zone	Definition of Outer Boundary	Maximum Depth of Wastewater Soakaway Pits	Domestic Controls	Industrial Controls
1	300-day travel time	none allowed	no new housing; no changes to existing wastewater disposal	no new industrial development
2	600-day travel time	6.5 m	septic tank with separate soakaway pits, for toilet effluent and other domestic wastewater, no storm runoff to sewage soakaway pits, no new fuel tanks	all liquid industrial waste to disposal specified by Water Authority with maximum soakaway pit depths as for domestic waste (zones 2–4)
3	5–6 year travel time	13 m	as above for domestic wastewater, fuel tanks subject to approved leakproof design	
4	other areas	no limit	no restrictions on domestic wastewater disposal, fuel tanks approved subject to leakproof design	

Table 2.1 Factors determining the shape and extension of groundwater supply protection areas*

PROTECTION AREA	CONTROLLING FACTORS
Overall Location and Shape	aquifer recharge and flow regime (recharge area/boundaries, natural discharge areas, hydraulic condition of streams**, aquifer boundaries, aquifer confinement, aquifer hydraulic gradients) presence of other pumping wells/boreholes**
Area of Supply Capture Zone	protected/licensed annual abstraction rate annual groundwater recharge rate(s)**
Perimeter of Inner Flow-Time-Based Zones (50-day and 500-day isochron)	aquifer transmissivity distribution aquifer dynamic flow thickness*** aquifer (effective) dynamic porosity***

* excludes manmade changes in groundwater regime due to urban construction and mining activities

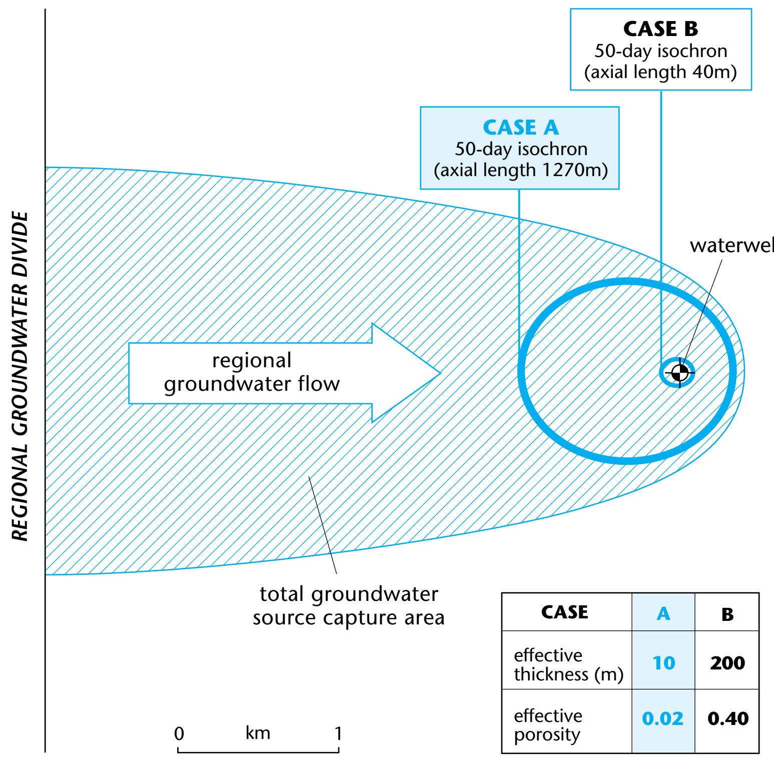
** these factors are generally time variant in nature and will provoke transient changes in the form of capture zones and isochrons, but average (or in some instances worst case) values are taken in steady-state formulations

*** termed dynamic in view of the fact that in heterogeneous (and especially fissured) aquifers, only a part of the total thickness and/or porosity (and in some cases only a minor part) may be involved in the flow regime to the groundwater supply source concerned

Microbiological protection zones are generally of fairly simple geometry, tending to be ellipsoidal or circular in form reflecting the cone of pumping depression around an abstraction borehole. For fissured aquifers the areal extent of these zones is very sensitive to the values taken for effective aquifer thickness and dynamic porosity (Figure-2.4), while their shape is sensitive to aquifer hydraulic conductivity.

The key factors determining the geometry of overall source capture zones are the aquifer recharge regime and boundary conditions (Adams and Foster, 1992); their shape can vary from very simple to highly complex. More complex shapes may be the result of variable groundwater/river interactions, the interference effects from other groundwater abstractions and/or lateral variations in hydraulic properties. Long narrow protection zones will be delineated where the supply source is located at large distance from aquifer boundaries and/or where the abstraction rate is small, the hydraulic gradient is steep and the aquifer transmissivity is high.

Figure 2.4 Sensitivity of 50-day transit-time perimeter to interpretation of fissured aquifer properties



CASE	A	B
effective thickness (m)	10	200
effective porosity	0.02	0.40

2.3 Limitations to Supply Protection Area Concept

The supply protection area (SPA) concept is a simple and powerful one, which is readily understood by land-use planners and others who need to make the often difficult public decisions generated by groundwater protection policies. However, many technical challenges can be posed by those who demand either greater protection or less restriction, and the test of any concept is whether it deals fairly with these competing criticisms, in the context of the circumstances it has to address (Foster and Skinner, 1995).

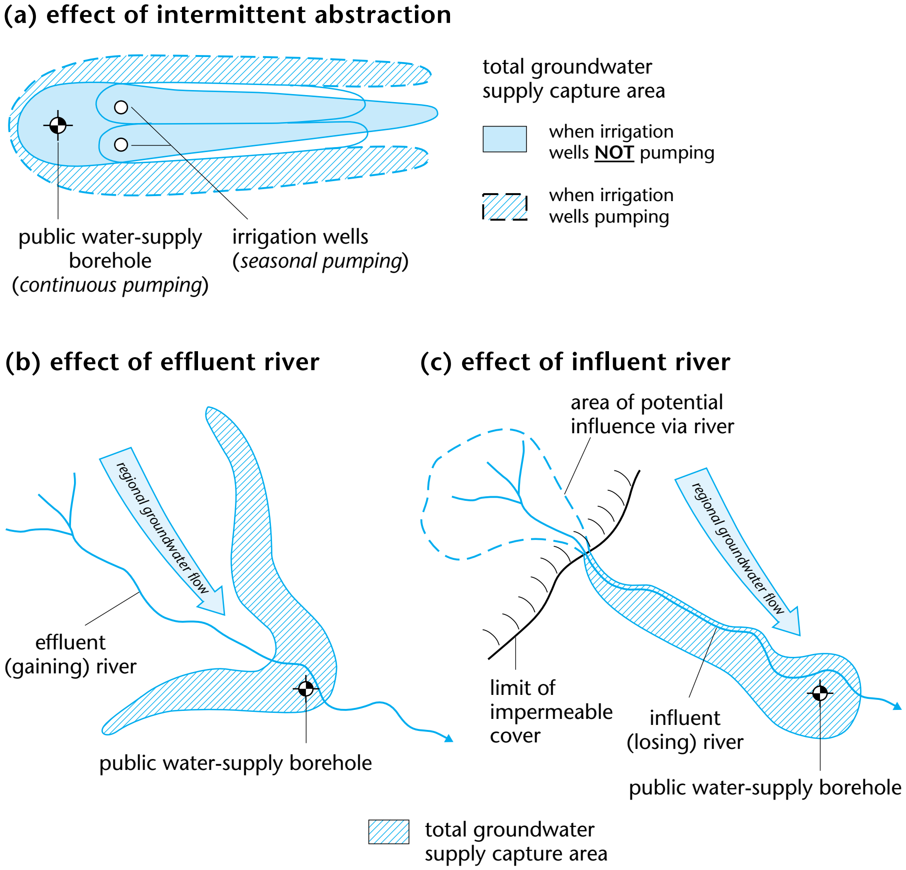
SPAs are most easily defined and implemented for major municipal wells and wellfields in relatively uniform aquifers that are not excessively exploited, but it is a valuable and instructive exercise to attempt to define them regardless of local conditions and constraints.

(A) Common Problems with Suggested Solutions

There are a number of hydrogeological situations where the concept encounters significant complications:

- the most serious limitation arises when aquifers are subject to heavy seasonally

Figure 2.5 Effect of various types of hydraulic interference and boundaries on the shape and stability of groundwater supply capture areas



variable pumping for agricultural irrigation or industrial cooling, since interference between pumping wells produces excessively complex and unstable protection zones (Figure 2.5a); recourse to overall resource protection via aquifer vulnerability criteria may then be the only feasible approach

- for aquifers whose long-term abstraction considerably exceeds their long-term recharge, a condition of continuously falling groundwater levels and inherently unstable SPAs arises
- the presence of surface watercourses gaining intermittently or irregularly from natural aquifer discharge can produce similar complications (Figure 2.5b)
- where losing surface watercourses are present within the capture zone to a supply source, any potentially polluting activity in the surface water catchment upstream of the recharge capture area could affect groundwater quality (Figure 2.5c), although it will usually be impractical to include this catchment in the source protection area
- special problems arise, especially with the definition of recharge capture areas, in situations where the groundwater divide is at a great distance and/or the regional hydraulic gradient is very low, and it will often be necessary to adopt a cut-off isochron (of 10 years)

- the presence of multi-layered aquifers, where vertical hydraulic gradients may develop inducing vertical leakage between aquifer units; each multi-layered aquifer situation will need to be examined on a site-by-site basis and some simplifying assumptions on hydraulic behavior made
- where the annual variation of the source capture area is very large (as in low-storage aquifers), the maximum (rather than average) area might be more appropriate, and local modifications may thus be required
- small groundwater supplies (with yields of less than 0.5 Ml/d) because in some situations their capture areas will be very narrow and of unstable locus.

Some may regard the 50-day travel-time criterion as excessively conservative because it takes no account of the large time-lag during percolation down the vadose zone, but in reality this needs to be balanced against the following factors:

- the possibility of rapid preferential flow through fissures, which can significantly reduce the retardation normally associated with vadose zone transport
- the isochron is calculated using mean saturated flow velocities, derived from average local aquifer properties and hydraulic gradients, and in fissure-flow aquifers a proportion of the water will travel much more rapidly than the average
- some contaminants may enter the ground with significant hydraulic loading (via drainage soakaways) and others (such as dense immiscible organic solvents) may have physical properties that favor more rapid penetration into the ground than water
- there is significant scientific evidence that some more environmentally hardy pathogens (such as Cryptosporidium oocysts) can survive much longer than 50 days in the subsurface (Morris and Foster, 2000).

(B) Case of Karstic Limestone Aquifers

Flow patterns in karstic limestone aquifers are extremely irregular due to the presence of dissolution features (such as caves, channels, and sinks), which short-circuit the more diffuse flowpaths through the fractured media as a whole. Contaminants moving through such a system can travel at much higher velocities than those calculated by average values of the aquifer hydraulic properties on an "equivalent porous media" approach. This simplification can be valid if the scale of analysis (and modelling) is regional, and if known major dissolution cavities associated with faults, or other structural features, are included, but in other cases the assumption can be misleading.

Where karstic features are present, they should be systematically mapped through field reconnaissance, aerial photograph interpretation, and (possibly) geophysical survey, at least in the vicinity of the springs or wells to be protected. Knowledge gained through local hydrogeological investigation (especially using artificial tracer tests and/or environmental isotopes) and speleological inspection should be also used on a site-by-site basis for protection area delineation, rather than using average aquifer properties and hydraulic gradients for the calculation. It must be accepted that major departures from normal zone geometry should be expected (Daly and Warren, 1998) and that known surface solution

Box 2.2

Delineation of groundwater supply protection zones for land-use planning in Esperanza, Argentina

The delineation of groundwater capture and flow-time zones, together with the mapping of aquifer pollution vulnerability, is an essential component of water source protection and land-use planning at the municipal level.

- The town of Esperanza (Sante Fe Province) meets its water demand entirely from groundwater. Locally, the semi-confined aquifer is intensively exploited not only to meet these demands, but also for agricultural irrigation and for a neighboring industrial center.

- The town's groundwater sources comprise:
  - a wellfield in a rural setting, where no land-use regulations or restrictions exist
  - a number of individual wells within the urban area, which has incomplete sanitary infrastructure and various industrial premises and services.

This situation, coupled with an aquifer pollution vulnerability rated as moderate by the GOD methodology, suggested the existence of a significant groundwater pollution hazard and the need for the introduction of protection measures including land-use planning.

For this purpose a range of possible protection perimeters were delineated for the 20 municipal wells, employing the WHPA semi-analytical method using groundwater travel times up to 5 years, as a basis for recommending graduated measures of aquifer pollution control and land-use restriction (Paris and others, 1999).

The implementation of groundwater source protection areas, however, is not a straightforward task, and it may be strongly resisted by those industries for which severe constraints or total relocation are proposed (as a result of their character). Such actions can prove difficult to achieve in view of their socioeconomic repercussions. Because of these considerations and with the object of facilitating improved levels of groundwater source protection, the alternative strategy of relocating groundwater abstraction to a new wellfield outside the area of urban influence has been proposed. The perimeters of protection for the proposed wellfield would then be delineated, with legal provision and technical regulations being introduced to guarantee their effectiveness. A groundwater monitoring network would also be established for the early detection and remediation of any potential problems.

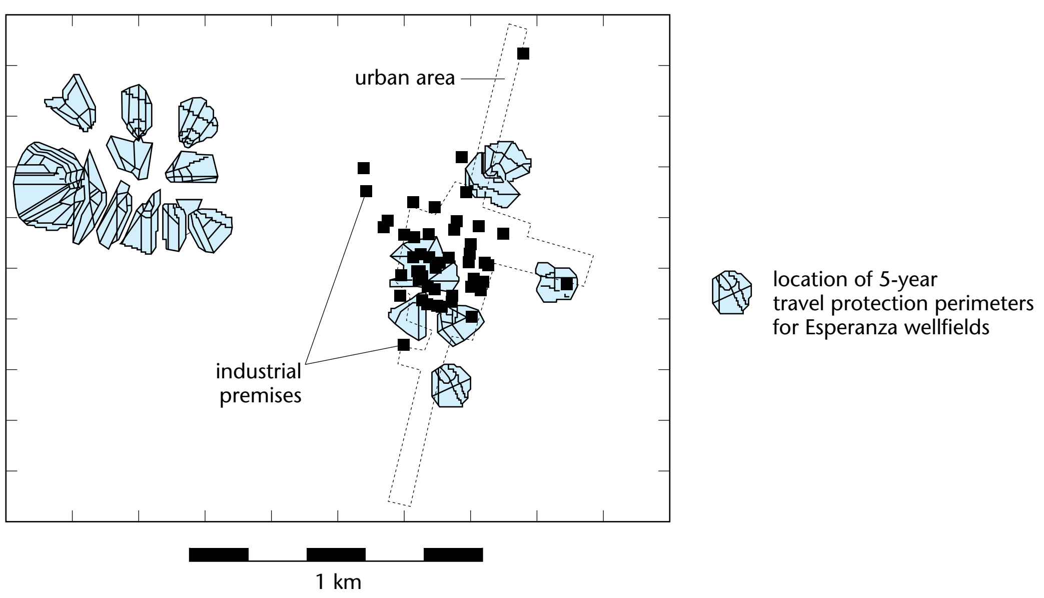
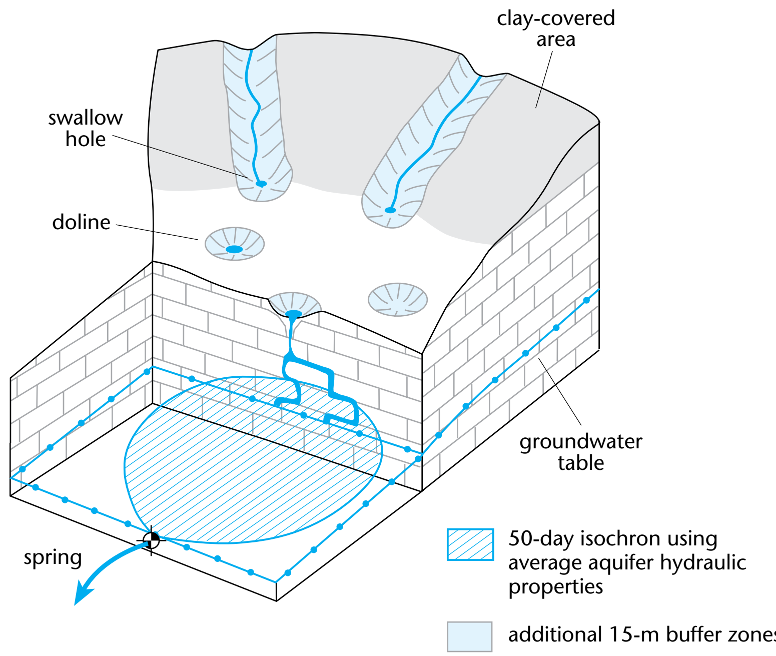


Figure 2.6 Adaptation of microbiological protection perimeters for the case of karstic limestone aquifers



features at large distances from the supply source, and the surface water catchment draining to them, will also warrant special protection (Figure 2.6).

(C) Case of Spring and Gallery Sources

In some places groundwater abstraction takes place from springs, that is from points of natural discharge at the surface. Springs present special problems for protection area delineation in that the abstraction is governed by natural groundwater flow driven by gravity. The size of the capture area is thus dependent on the total flow to the spring, rather than the proportion of the flow actually abstracted. Springflow may be intermittent, reducing drastically or even drying-up in the dry season as the water table falls. Springs often occur at the junction of geological discontinuities, such as lithology changes, faults or barriers, the nature and extent of which may be at best only partially understood.

Moreover, there may also be considerable uncertainty on the actual location of springs, given the presence of infiltration galleries and pipe systems. Inevitably for all these cases, rather approximate, essentially empirical, and somewhat conservative assumptions have to be made in the delineation of protection perimeters (Figure 2.2).

The delineation of protection zones around well sources can also be complicated by the presence of galleries (or adits), which distort the flow-field by providing preferential pathways for water movement; empirical adjustment is normally the method used to deal with this problem, although numerical modelling may also be an aid where sufficient data are available.

(D) Implementation in Urban Settings

The concept of groundwater supply capture areas and flow zones is equally valid in all environments, but substantial problems often occur in both their delineation through hydrogeological analysis and their implementation as protection perimeters in the urban environment. This results from the complexity of aquifer recharge processes in urban areas, the frequently large number of abstraction wells for widely differing water uses and the fact that most of the SPAs defined will already be occupied by industrial and/or residential development.

Nevertheless, the zones delineated will serve to prioritize groundwater quality monitoring, inspection of industrial premises and groundwater pollution mitigation measures (such as changes in industrial effluent handling or chemical storage and introduction of mains sewer coverage in areas of high aquifer pollution vulnerability).

2.4 Methods for Definition of Protection Zone Perimeters

The delineation of perimeters of source protection zones can be undertaken using a wide variety of methods (Table 2.2), ranging from the oversimplistic to extremely elaborate. Historically, arbitrary fixed-radius circular zones and highly simplified, elliptical shapes have been used. However, due to the obvious lack of a sound scientific foundation, it was often difficult to implement them on the ground, because of their questionable reliability and general lack of defensibility.

Table 2.2 Assessment of methods of delineation of groundwater supply protection areas

METHOD OF DELINEATION	COST	RELIABILITY
	lowest	least
Arbitrary Fixed/Calculated Radius	↑	↑
Simplified Variable Shapes		
Analytical Hydrogeological Models		
Hydrogeological Mapping		
Numerical Groundwater Flow Models (with particle tracking routines for flowpath definition)	↓	↓
	highest	most

Emphasis will thus be put here on two methodological options:

- simple, but scientifically based, analytical formula, tools, and models
- more systematic aquifer numerical modelling

but the choice between them will depend more on hydrogeological data availability than any other consideration.

In both cases it is essential to reconcile the zones defined with local hydrogeological conditions, as depicted by hydrogeological maps. The delineation process is highly dependent upon the reliability of the conceptual model adopted to describe the aquifer system and on the amount and accuracy of data available. However, the geometry of the protection zone defined will also be influenced by the method used for its delineation.

It must be remembered that the delineation of protection perimeters, like the groundwater regime it operates on, is a dynamic system. No zone is immutable, because groundwater conditions may physically change or because new hydrogeological data may come to light that enable the aquifer to be more accurately represented. Equally, while accepting that many groundwater flow systems show complex behavior in detail (especially very close to wells), such local complexities are less critical at the scale of protection zone delineation. And in most situations, existing simulation techniques applied to sound aquifer conceptual models provide acceptable results.

In general terms the reliability of source protection areas decreases with increasing time of groundwater travel in the aquifer. For example, the 50-day flow-time perimeter usually shows little variation between different methods of delineation, but the 10-year flow-time perimeter can vary by many ha's or even km^2 with great divergence of shape.

Recent developments have made groundwater models more widely available, more user-friendly and with improved visual outputs. Several public domain codes, such as the analytical model WHPA can now be downloaded from websites. And user-friendly interfaces such as FLOWPATH or Visual MODFLOW are now available for widely tested numerical flow models, such as MODFLOW, incorporating particle tracking techniques such as MODPATH (Livingstone and others, 1985). As a result, hydrogeologists worldwide have easier access to sophisticated, yet easy to use, modelling techniques (Table 2.3).

(A) Analytical versus Numerical Aquifer Models

Analytical tools and models apply relatively simple analytical formula to simulate groundwater flow, normally in two dimensions. Models such as WHPA are easy to use, require little information, and many codes are available free on websites. However, analytical models are essentially limited to various assumptions (such as homogeneous aquifer properties and thickness, infinite aquifer extent, etc.) that prevent their use in more complex field conditions. They are, however, a good option for areas with limited hydrogeological data and relatively uniform aquifer systems.

Table 2.3 Useful website addresses on numerical groundwater modelling for source protection

ORGANIZATION	WEBSITE ADDRESS
International Association of Hydrogeologists	http://www.iah.org/weblinks.htm#softw
International Ground Water Modelling Center	http://www.mines.edu/igwmc/
National Groundwater Association	http://www.ngwa.org/
EPA Center for Subsurface Modelling Support	http://www.epa.gov/ada/csmos.html
USGS Water Resources Applications Software	http://water.usgs.gov/software/

Numerical models are technically superior in that they can accommodate complex variations in aquifer geometry, properties, and recharge patterns, thus giving results closer to reality. However, they do require more data and are more time-consuming. Numerical aquifer modelling is recommended for areas where reasonable hydrogeological data are available and hydrogeological conditions cannot be readily simplified to the point required for the utilization of analytical modelling codes. Furthermore, numerical models can be readily used to evaluate the effects of uncertainties on the shape and size of protection zones and as predictive tools to assess future abstraction scenarios and hydrological system impacts.

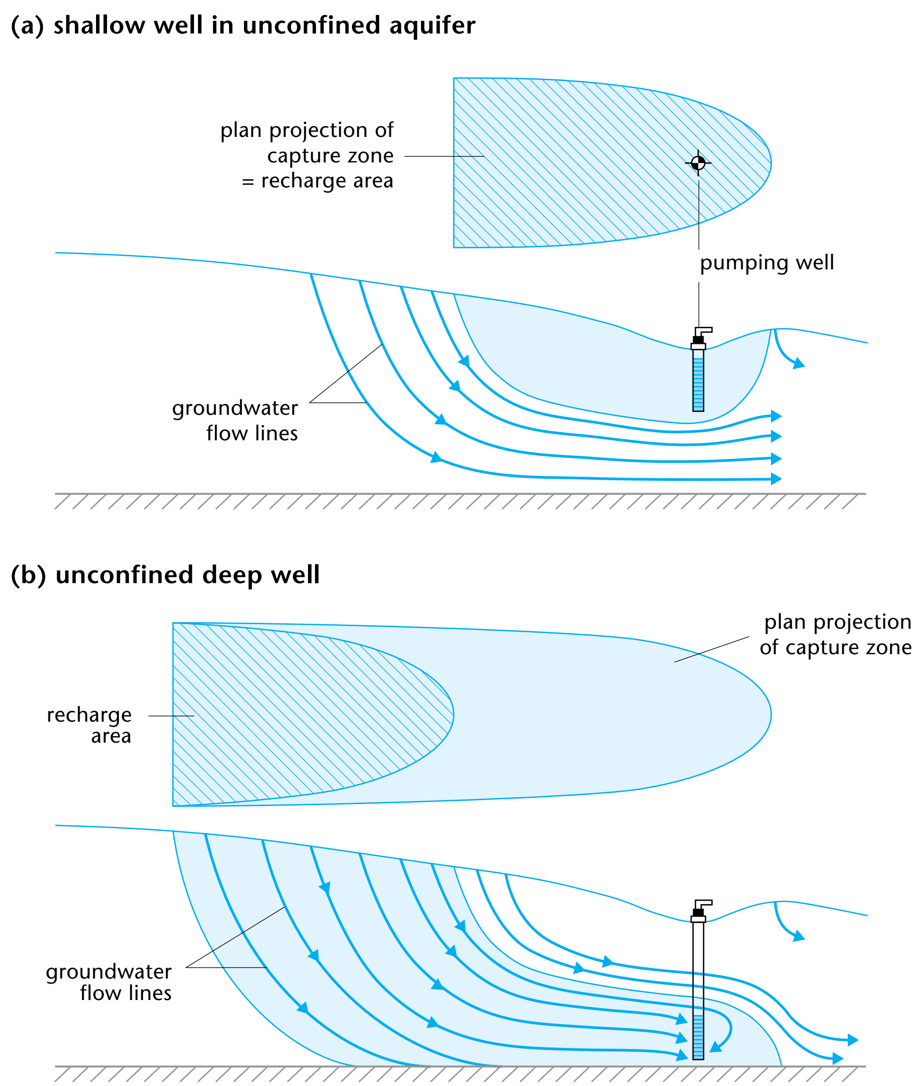
Such models may be based on finite difference or finite element codes. Finite difference methods use variable-spaced rectangular grids for system discretization, and are easy to understand, computationally stable and widely used, but may encounter difficulties in adjusting to complex geological boundaries. Finite element codes use triangular or prismatic elements that adapt well to irregular geology, but localized mass balance problems may occur.

Where possible numerical aquifer models, employing a particle-tracking routine, are preferred. In these the movement of groundwater toward a source during pumping can be tracked numerically in small time-steps. Particle tracking produces flowlines emanating from the source in different directions, and the total capture perimeter under steady-state flow conditions is determined by the extent of the pathlines at infinite time and must continue to a point of zero flow velocity or the edge of the area under study. Particle tracking techniques form the basis for protection zone delineation, since most particle tracking codes are able to undertake velocity calculations within the flow-field, permitting isochron definition. It should be noted, however, that only advective (nondispersive) flow is simulated by particle tracking codes.

(B) 2-D versus 3-D Aquifer Representation

In order to apply numerical models to represent actual aquifer systems several simplifications are made. One of the most common is the transformation of a complex three-dimensional system to a simplified two-dimensional model, since in most cases there are not enough hydrogeological data (in terms of aquifer vertical permeability values and hydraulic head variations) to characterize and calibrate the vertical groundwater flow components. Given this and the fact that most aquifers are relatively thin compared to their aerial extension,

Figure 2.7 Comparison between total capture area of idealized wells with shallow and deep intake in an unconfined aquifer showing the theoretical influence of vertical flow



two-dimensional models are usually adequate and much more commonly used. However, in cases where vertical fluxes are important, two-dimensional flow modelling may overestimate the dimensions of capture zones, and therefore produce larger protection areas (Figure 2.7). Thus three-dimensional flow models are, in the future, likely to be increasingly used for complex aquifer systems if sufficient data are available.

(C) Practical Considerations

There are a number of distinct steps in the process of protection zone delineation. The most important stage in the whole process is probably data acquisition. Information is required not only on aquifer properties, but also on well construction, source operational regime, groundwater levels, recharge processes, and rates, and the aquifer interaction with surface watercourses. No source protection zones can be delineated in isolation, and all require the consideration of the groundwater unit involved, at least to a radius of 5 km and more normally 10 km.

When the basic data have been compiled, all available information should be synthesized into a conceptual model with the objective of providing a clear statement of the groundwater setting. This can then be used either as the basis for analytical zone definition or to guide the numerical modeller in setting up a simulation of the actual groundwater conditions. The choice of delineation technique will be a function of:

- the degree of understanding of the groundwater setting involved
- the operational importance of the groundwater supply concerned
- the human and financial resources available.

Integrated GIS and databases provide a useful means of organizing the data within a single system, and provide the visualization powers to cross-check for inconsistencies and to model geographically distributed data.

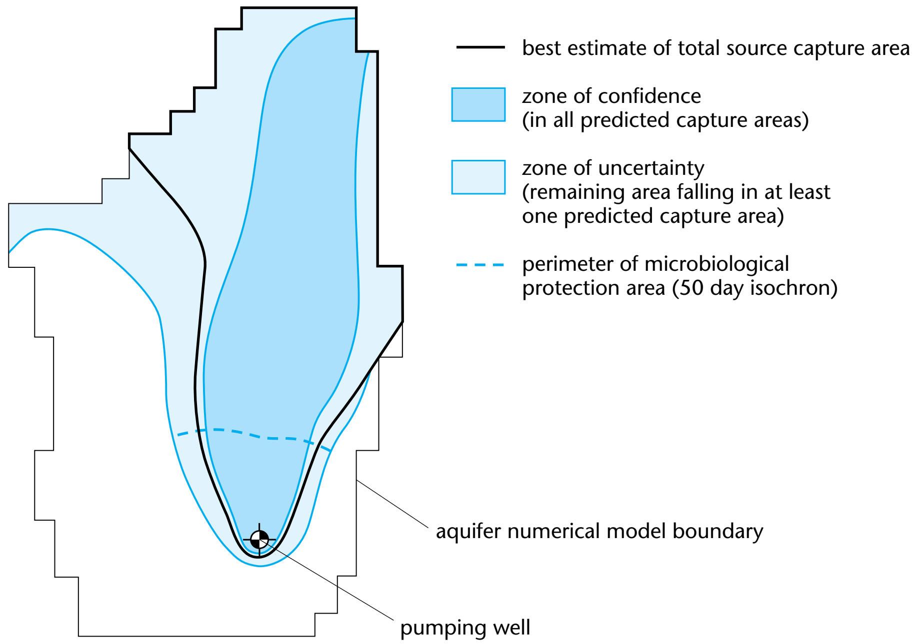
2.5 Dealing with Scientific Uncertainty

A numerical aquifer model can only be as good as its input data and the conceptual understanding of the groundwater flow regime. The size, shape, and location of source protection areas is largely controlled by hydrogeological parameters, which are often inadequately quantified. It follows that confidence in the predicted zones will be limited by uncertainty in the parameters involved.

Models have to be calibrated by comparing model outputs to observed aquifer head conditions. A sensitivity analysis should be performed, in which key input parameters are systematically varied within reasonable ranges, and the effects of such variations on capture zone and flow time perimeters established.

The most rigorous approach to sensitivity analysis is to use a Monte Carlo (statistically based) approach, to define the maximum protection perimeter, which is the envelope of all credible

Figure 2.8 Practical approach to incorporation of hydrogeological uncertainty into delineation of groundwater source protection areas



zones. By itself this approach is only likely to be acceptable in public policy terms where protection of groundwater is of overriding importance. In most circumstances, however, there are balances of interest to be struck that do not accept a zero-risk approach. The question of uncertainty must not be dismissed, however, because it is important that stakeholders understand the basis on which protection zones are defined.

The numerical groundwater model used will be based on the best estimate of parameter values, and the best-fit protection zones defined are the only ones to meet the groundwater balance criterion. However, any model must inevitably be open to uncertainties, because it is physically impossible to verify in the field all the parameters represented by the simulation. The most critical variables affecting protection zone geometry are aquifer recharge rate, hydraulic conductivity, and effective porosity (Table 2.1). Best estimate and credible limit values for each of these variables can be determined from available data and all combinations that achieve acceptable hydraulic head distributions are used to compile an envelope for each protection areas. From this envelope the following can be defined (Figure 2.8):

- Zone of Confidence: defined by the overlap of all plausible combinations
- Zone of Uncertainty: the outer envelope formed by the boundaries of all plausible combinations.

The parameters usually varied to allow the construction of the two zones are aquifer recharge and hydraulic conductivity. Acceptable ranges of these two parameters are established by varying them systematically around the best estimate value, running the model, and noting the bounds within which the calibration targets are satisfied. Sensitivity runs, using parameter values from within the acceptable range, are subsequently carried out to compile the above zones. In a typical, well-calibrated model, recharge and hydraulic conductivity multipliers to the best estimate in the range 0.8–1.2 and 0.5–5.0, respectively, are applied universally across the model. An additional set of model runs using multipliers for effective porosity normally in the range 0.5–1.5 are carried out; the resulting travel-time zones are invariably more uncertain than the source capture area, because of the influence of this additional uncertain parameter.

New automated parameter estimation programs (such as MODFLOW-P or PEST) are becoming an integral part of conducting systematic parameter uncertainty analysis. These inverse-model routines use complex algorithms to estimate the best input parameters for matching observed heads and fluxes. Professional judgement is essential in using such codes, however, since no hydrogeologically based interpretation is performed by them.

Overall parameter uncertainty should be a major consideration when delineating groundwater capture zones, and the identification of those areas that are definitely (or possibly) contributing to a given supply source is an important tool in the definition of groundwater protection strategies. However, it must be noted that the methodology described above does not take account of errors arising from the use of inappropriate conceptual and/or numerical aquifer models, and expert judgement in this regard remains critical to overall zone modelling and uncertainty assessment.

2.6 Perimeter Adjustment and Map Production

Once groundwater source protection zones have been delineated, the results should be inspected to assess whether adjustments are needed. Empirical adjustments are often required to provide protection zones that are both robust and credible in application.

The output from the delineation process has to be translated into final source protection area maps, which can be superimposed on aquifer vulnerability maps for the purpose of groundwater supply pollution hazard assessment. This stage involves a sequence of modifications to the computed outputs, which experience has shown is probably best carried out with CAD software. The general sequence is as follows:

- final checks that the zones meet the minimum criteria in the definitions
- adjustment of boundaries to deal with problems of scale, and where possible, to make model boundaries conform with actual field property boundaries
- map production and reproduction, at scales in the range 1–25,000 to 100,000.

When drawing protection zone boundaries, actual hydrogeological features should be used rather than model boundaries wherever possible. A sound general convention is to draw and label actual boundaries where these are known and indicate model boundaries where they are indistinct, with suitable labelling to make this clear to the map user.

A further degree of judgement is often required when dealing with confining layers; where there is a proven, substantial confining layer around a source, the microbiological protection zone is limited to a radius of 50-meters. However, where there are known or planned major manmade subsurface structures (such as road tunnels or mine access shafts) the full 50-day zone should be shown. Where a low permeability confining layer or cover occurs around the source, its extension is identified on protection zone maps using hatched shading, to indicate some uncertainty especially if it was not taken as an area of zero rainfall recharge in the numerical modelling.

Protection zones with long thin tails may arise due to pumping interference from other boreholes and/or from the imprecision of computer-model zone delineation. Wherever such features arise, they should be truncated at a minimum radius of 50-meters. This is an arbitrary but consistent measure preventing maps from appearing spuriously precise.

B3

Inventory of Subsurface Contaminant Load

In any program of groundwater quality protection, knowledge of potential sources of contamination is critical because it is these that generate the emission of contaminants into the subsurface environment. This chapter presents a systematic approach to the survey of subsurface contaminant load.

3.1 Common Causes of Groundwater Pollution

General review of known incidents of groundwater pollution leads to the following important observations, which are of relevance despite the fact that most published work refers to the more industrialized countries and may not be fully representative of those in the earlier stages of economic development:

- a large number of anthropogenic activities are potentially capable of generating a significant contaminant load, although only a few types of activity are generally responsible for the majority of serious cases of groundwater pollution (Table-3.1)
- the intensity of aquifer pollution is not normally a direct function of the size of the potentially polluting activity on the overlying land surface; in many instances smaller industrial activities (such as mechanical workshops) can cause a major impact on groundwater quality. These are widely distributed, often use appreciable quantities of toxic substances, sometimes operate outside formal commercial registers or are clandestine, and thus not subject to normal environmental and public health controls
- more sophisticated, large-scale industries generally exert more control and monitoring over the handling and disposal of chemicals and effluents, to avoid off-site problems due to inadequate effluent disposal or accidental spillages of stored chemicals
- because of unstable economic conditions, it is relatively commonplace for small

Table 3.1 Summary of activities potentially generating a subsurface contaminant load

TYPE OF ACTIVITY	distribution category	CHARACTER OF POLLUTION LOAD main types of pollutant	hydraulic surcharge	soil zone bypass
			(+ indicates increasing importance)	
Urban Development				
unsewered sanitation	u/r P–D	n f o t	+	+
leaking sewers (a)	u P–L	o f n t	+	
sewage oxidation lagoons (a)	u/r P	o f n t	++	+
sewage land discharge (a)	u/r P–D	n s o f t	+	
sewage to losing river (a)	u/r P–L	n o f t	++	++
leaching refuse landfill/tips (a)	u/r P	o s h t		+
fuel storage tanks	u/r P–D	t		
highway drainage soakaways	u/r P–D	s t	+	++
Industrial Production				
leaking tanks/pipelines (b)	u P–D	t h		
accidental spillages	u P–D	t h	+	
process water/effluent lagoons	u P	t o h s	++	+
effluent land discharge	u P–D	t o h s	+	
effluents to losing river	u P–L	t o h s	++	++
leaching residue tips	u/r P	o h s t		
soakaway drainage	u/r P	t h	++	++
aerial fallout	u/r D	s t		
Agricultural Production (c)				
a) crop cultivation				
– with agrochemicals	r D	n t		
– with irrigation	r D	n t s	+	
– with sludge/slurry	r D	n t s o		
– with wastewater irrigation	r D	n t o s f	+	
b) livestock rearing/crop processing				
– effluent lagoons	r P	f o n t	++	+
– effluent land discharge	r P–D	n s o f t		
– effluent to losing river	r P–L	o n f t	++	++
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 nonindustrial areas
(c) intensification presents main pollution risk
u/r urban/rural
P/L/D point/line/diffuse

n nutrient compounds
f fecal pathogens
o overall organic load
s salinity
h heavy metals

t toxic micro-organisms
\+ increasing significance

industrial enterprises to open and close over short time periods, which complicates the identification and control of potentially polluting activities and may leave a legacy of contaminated land

- the quantity of potentially polluting substances used in industry does not bear a direct relationship with their occurrence as groundwater contaminants, and it is the subsurface mobility and persistence of contaminant species that is the key factor (Table-3.2)

Table 3.2 Most common types of groundwater contaminant found during intensive surveys in industrial nations

a) The Netherlands: 500 important sites of contaminated land (Duijvenboden, 1981)

Pollution Source	Types of Contaminant	Frequency of Occurrence (%)
Coal Gas Works	aromatic hydrocarbons (BTEX group) phenols, cyanide	28
Waste Tips and Sanitary Landfills	variable, often ammonium, chlorinated hydrocarbons, heavy metals, alkylbenzene, domestic/industrial pesticides, etc.	21
Metal Industries	chlorinated hydrocarbons, heavy metals	12
Hydrocarbon Storage and Handling	aromatic hydrocarbons (BTEX group), lead	8
Chemical Plants	wide range of halogenated and aromatic hydrocarbons, phenols, alkylbenzene, etc.	7
Paint Factories	aromatic hydrocarbons (BTEX group), chlorinated hydrocarbons	5

b) USA: 546 monitoring sites on priority aquifers (Ref. ASTM, 1995)

Types of Contaminant	Frequency of Occurrence (%)
trichloroethylene	6
lead	5
toluene	5
benzene	5
polychlorinated biphenyls	4
chloroform	4
tetrachloroethylene	3
phenols	3
arsenic	3
chromium	3

- relatively small amounts of more toxic and persistent chemical compounds are capable of generating large groundwater contamination plumes, particularly in aquifer systems characterized by high groundwater flow velocities
- the nature of the polluting activity (particularly in terms of contaminant type and intensity) can, in some cases, exert an overriding influence on the groundwater quality impact regardless of aquifer vulnerability.

It is therefore possible to conclude that certain sorts of anthropogenic activity, which tend to be associated with specific contaminant types, represent the greatest threat to aquifers. Thus a systematic inventory and classification of potential contaminant sources is a key step in programs of groundwater pollution hazard assessment and quality protection.

3.2 Basic Data Collection Procedures

(A) Designing a Contaminant Load Inventory

Drawing up an inventory of potentially polluting sources includes systematic identification, siting, and characterization of all such sources, together with obtaining information on their historical evolution where appropriate and feasible. Such information will serve as a foundation for the assessment of which activities have the greatest potential for generating a potentially hazardous subsurface contaminant load. There is a common basis for all studies of this type, but local socio-economic conditions will also exert a significant influence on the approach that can and should be adopted.

The inventory of potentially polluting activities (Figure-3.1) can be divided into three stages (Zaporozec, 2001):

Figure 3.1 Development of an inventory of potential sources of subsurface contaminant load

	A	B	C	D
(1) Inventory Design	Identification of Inventory Objectives and Area Characteristics	Identification of Data Sources and Assessment of Available Data	Consideration of Financial Resources and Available Personnel	Determination of Scope of Inventory and Selection of Methods
(2) Inventory Implementation	Organization of Inventory Team and Preparation of Maps and Proformas	Inventory of Contamination Sources and Existing Contamination	Verification of Data and Preliminary Classification and Ranking of Sources	Assessment of Needs for Additional Data and Completion of Field Survey
(3) Evaluation Survey	Organization and Evaluation of Data	Evaluation and Rating of Sources	Map Production and Final Inventory	Pollution Control Recommendations

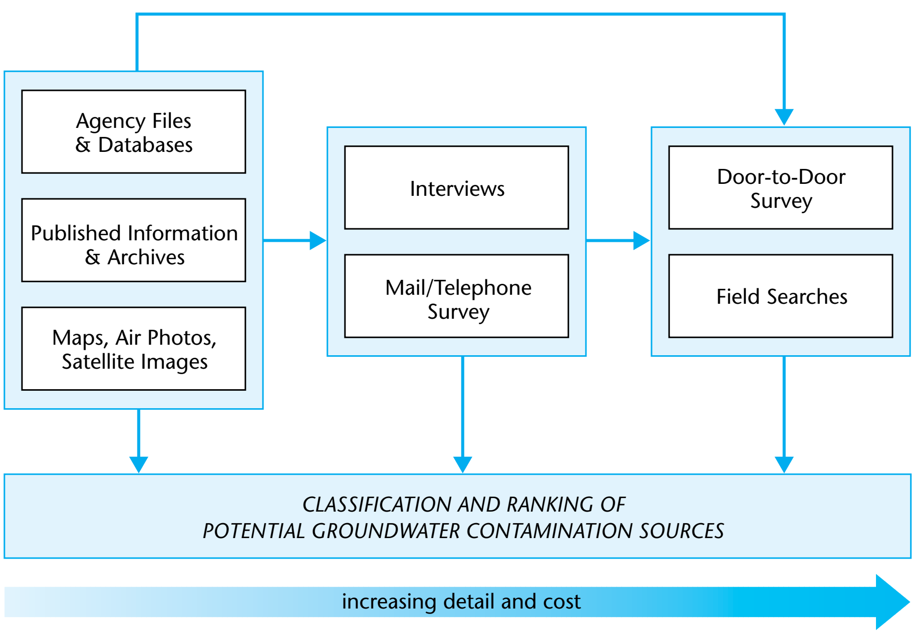
- inventory design, which includes the identification of information sources, the available financial budget, the level of technical personnel required, and the basic survey method
- inventory implementation, which includes the organization of the survey, the preparation of survey proformas, and the actual process of data acquisition
- survey evaluation, which includes the analysis of data generated, including verification of its consistency and reliability, the classification of polluting activities, and the construction of a database that can output information in map or GIS form.

The identification of information sources is particularly important to the work. In many instances most of the relevant data are held by provincial/municipal government organizations and by the private sector. Previous studies for other purposes can be valuable sources of summary information, as can telephone directories (Yellow Pages) and listings of industrial boards and associations. Archive aerial photographs and satellite images are a valuable basis for the generation of land-use maps, including historic changes. It is essential that the approach to identification of potential pollution sources be fairly conservative, because it would be wrong to discard or downgrade activities just because available information was insufficient.

There is a range (Figure 3.2) of inventory approaches (US-EPA, 1991):

- from exclusively desk-top evaluation of secondary data sources
- to basic field reconnaissance, in which teams survey selected areas to verify the existence of potential contamination sources.

Figure 3.2 Approaches to data collection for surveys of potential groundwater pollution sources



The type of inventory and the level of detail required has to be a function of the ultimate objective of the work program, the size of the area under study, the range of industrial activities present, the availability of existing data, the financial budget provision, and the technical personnel available.

The process of inventory ought to be undertaken on the basis of clearly defined, measurable and reproducible criteria, such that it is capable of generating a reasonably homogeneous dataset. For this reason it is preferable to base the design survey proformas and data-entry systems on a list of standardized questions and answers. As far as possible, some cross-checking of the consistency of information should be included.

(B) Characteristics of Subsurface Contaminant Load

From a theoretical viewpoint the subsurface contaminant load generated by a given anthropogenic activity (Figure 3.3) has four fundamental and semi-independent characteristics (Foster and Hirata, 1988):

- the class of contaminant involved, defined by its probable persistence in the subsurface environment and its retardation coefficient relative to groundwater flow
- the intensity of contamination, defined by the probable contaminant concentration in the effluent or leachate, relative to the corresponding WHO guideline value for drinking water, and the proportion of aquifer recharge involved in the polluting process
- the mode of contaminant discharge to the subsurface, defined by the hydraulic load (surcharge) associated with contaminant discharge and the depth below land surface at which the contaminated effluent or leachate enters is discharged or generated
- the duration of application of the contaminant load, defined by the probability of contaminant discharge to the subsurface (either intentionally, incidentally, or accidentally) and the period during which the contaminant load will be applied.

(C) Practical Survey Considerations

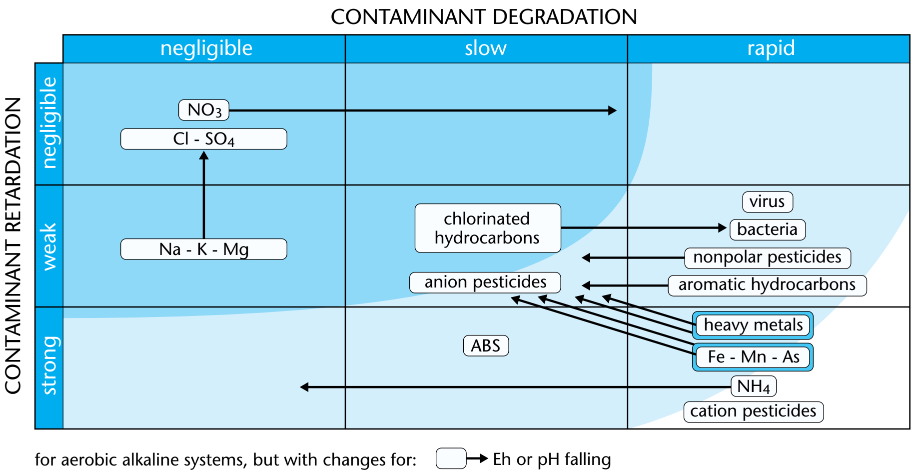
Ideally, information on each of the above characteristics for all significant potentially polluting activities is required. It would be even better if it were possible to estimate the actual concentrations and volumes of pollutant discharge to the subsurface. However, as a result of the great complexity, frequently high density, and considerable diversity of potential pollution sources, this ideal is not achievable in practice.

Nevertheless, the ideal data requirements (Figure-3.3) should not be ignored because they constitute the rational basis for a detailed study of subsurface contamination load, including effluent inspection and sampling and leachate monitoring, where detailed follow-up is justified (Foster and Hirata, 1988). More generally, all techniques of contaminant inventory and classification are subject to significant imperfections and limitations. Nevertheless, because of the impossibility of controlling all polluting activities, it is essential that a method be found that is capable of identifying those that present the greatest likelihood

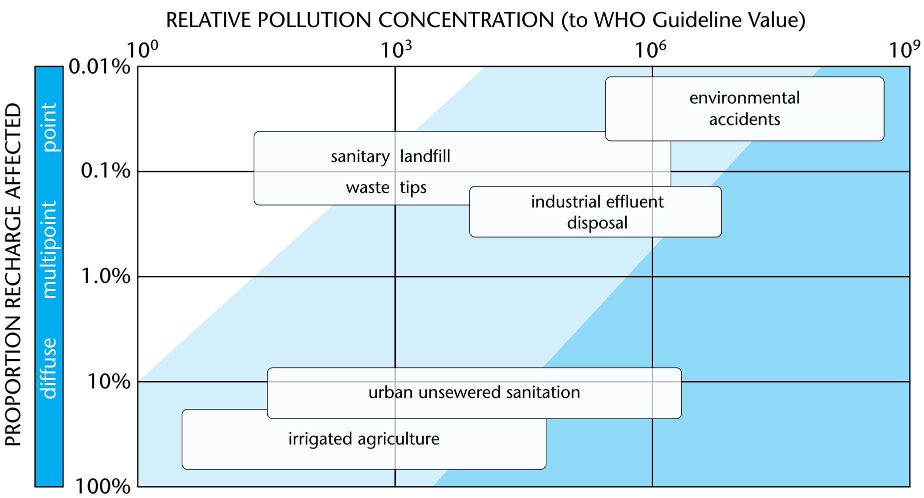
Figure 3.3 Characterization of components of subsurface contaminant load

(increasing scale of potential impact is indicated by the darker shading)

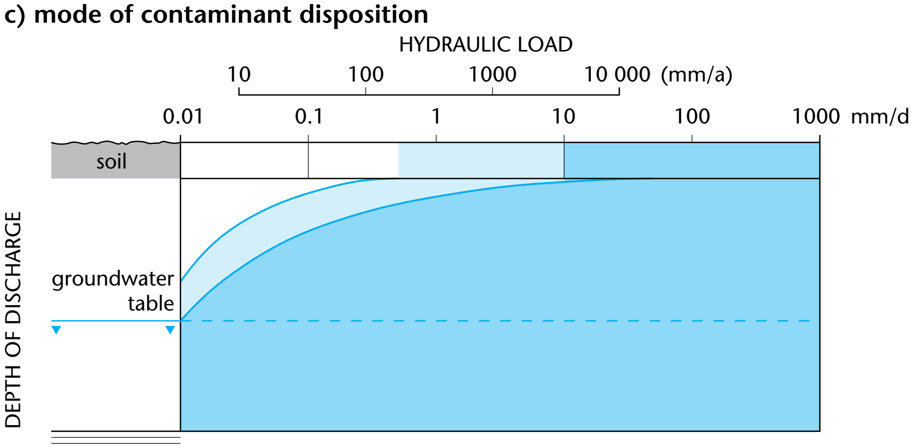
a) class of contaminant



b) intensity of contamination

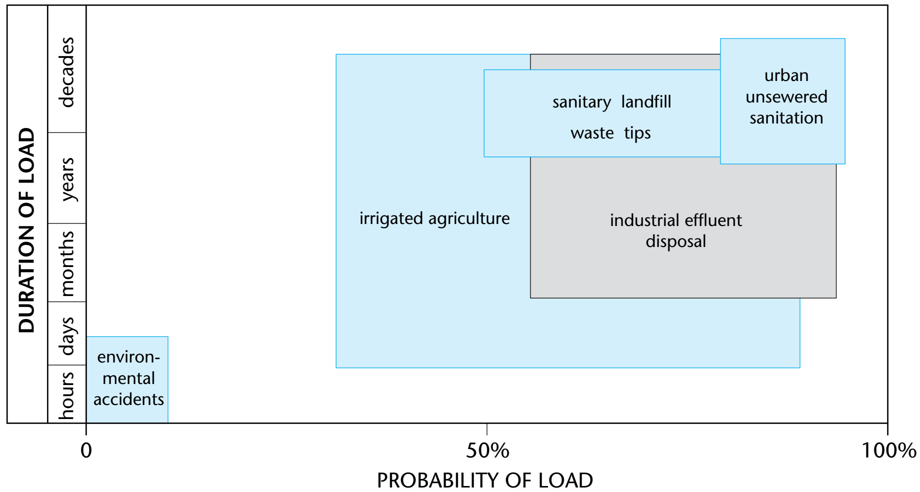


c) mode of contaminant disposition



continued ...

d) duration of contaminant load



of generating a serious subsurface contaminant load, so that priorities for control can be established.

Because of the frequent complexity in detail of land occupation and use, and related potentially polluting activities, clearly defined data collection criteria are required and special attention needs to be paid to the following:

- adjusting the scale of data representation to the available time and budget; it should be noted that general groundwater pollution hazard reconnaissance usually requires surveys at a scale of around 1:100,000 to superimpose on maps of aquifer pollution vulnerability, whereas more detailed scales 1:10,000–50,000 will be required for assessment and control of the pollution hazard to specific waterwells and springs
- ensuring that the outputs of survey work, in terms of the different origins of potential contaminant load, are at a compatible level of detail, with the aim of facilitating a balanced overall analysis of the area under study
- avoiding the indiscriminate mix of information of widely varying survey data, because this can lead to serious interpretation errors, and when this is not possible, to clearly record the limitations of the datasets in this respect
- taking a staged approach to the development of the register of potentially polluting sources, eliminating those with low probability of generating a significant subsurface contaminant load, before proceeding to more detailed work.

3.3 Classification and Estimation of Subsurface Contaminant Load

(A) Spatial and Temporal Occurrence

There are various published methods of assessing the pollution potential of anthropogenic activities, although few are directed to rating their potential to generate a subsurface

Box 3.1

Evaluation of the subsurface contaminant load generated by agricultural cultivation in São Paulo State, Brazil

Diffuse sources of subsurface contaminant load are difficult to monitor directly for a number of practical reasons. Nevertheless, reasonable estimates of potential leaching losses can be made indirectly given reliable data on agrochemical usage, cultivation regime, and soil types.

- São Paulo State in Brazil, with an area of some 250,000-square kilometers and a population of 33 million, is divided into some 560 municipal authorities. Groundwater resources play a major role in meeting its urban, industrial, and irrigation water demand. Agricultural activity occupies 83 percent of the land area with the cultivation of sugarcane, coffee, citrus, and maize dominant.

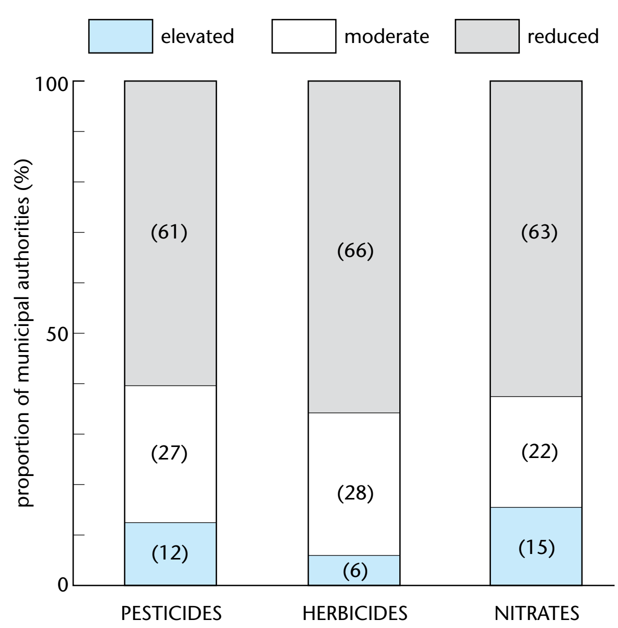
- In 1990 this agricultural activity used some 2.59 million tons of fertilizers (with phosphate applications being especially high) and some 0.07 million tons of pesticides (by active ingredient), making it the most intensive agricultural area in Brazil. Additionally, the majority of soils are acidic and some 1.10 million tons of lime a year are applied for soil conditioning and to reduce fertilizer leaching.

- For the purpose of measuring groundwater pollution hazard, the use of agrochemicals for crop production was assessed in terms of its potential to generate a subsurface contaminant load through soil leaching. This was done by a team from IGSP, CETESB, DAEE, and EMBRAPA. The following data were available and compiled: the cultivation type, the amount of various agrochemicals applied by crop, the properties of these agrochemicals, the soil characteristics in terms of texture and organic content, and the rainfall regime/irrigation application in terms of timing/volume of infiltration.

- Using these data, the potential for nitrate leaching was estimated on the basis of the continuity of crop cover and the generation and application of soil nitrate compared with plant requirements. The pesticide-leaching hazard was estimated on the basis of the types of compound used, their adsorption potential according to partition coefficient, and soil organic carbon content (Hirata and others, 1995). With data on a more detailed scale, a higher resolution assessment would be possible.

Class of Agrochemical	Principal Types	Main Crops Treated type	Main Crops Treated area (ha)
pesticide	metamidophos	cotton	325,300
	monocrophos	soya	459,300
	vamidoton	beans	452,630
	acephate		
herbicide	dalapon	soya	459,300
	simazine	sugar cane	1,752,700
	atrazine		
	bentazon		
	2,4-D		
nitrate	N fertilizers	sugar cane	1,752,700
		citrus	769,000
		pasture	n/a

Statistical summary of assessments of potential intensity of subsurface contaminant load



contaminant load; more emphasis is generally put on their river or air pollution hazard (Foster and Hirata, 1988; Johansson and Hirata, 2001).

The classification of potentially polluting activities by their spatial distribution provides a direct and visual impression of the type of groundwater contamination threat they pose and the approach to control measures that is likely to be required:

- diffuse pollution sources do not generate clearly defined groundwater pollution plumes, but they normally impact a much larger area (and thus volume) of aquifer
- point pollution sources normally cause clearly defined and more concentrated plumes, which makes their identification (and in some cases control) easier; however, when point-source pollution activities are small and multiple, in the end they come to represent an essentially diffuse source, as regards identification and control.

Another important consideration is whether the generation of a subsurface contaminant load is an inevitable or integral part of the design of an anthropogenic activity (for example as is the case with septic tanks) or whether the load is generated incidentally or accidentally (Foster and others, 1993). Another useful way of classifying polluting activities is on the basis of their historical perspective, which also exerts a major influence on the approach to their control:

- past (or inherited) sources of contamination, where the polluting process or the entire activity ceased some years (or even decades) before the time of survey but there is still a hazard of generating a subsurface contaminant load by the leaching of contaminated land
- existing sources of contamination, which continue to be active in the area under survey
- potential future sources of contamination, relating to activities at the planning stage.

(B) The POSH Method of Load Characterization

It is necessary to take into consideration these various forms of classification during the survey of potential sources of subsurface contaminant load. However, for the type of simplified inventory proposed for the purposes of this Guide, it is convenient to characterize the potential sources of subsurface contaminant load on the basis of two characteristics:

- the likelihood of the presence of contaminants, which are known or expected to be persistent and mobile in the subsurface
- the existence of an associated hydraulic load (surcharge) capable of generating advective transport of contaminants into aquifer systems.

Such information is not always readily available, and it is generally necessary to make the following further simplifying assumptions:

- associating the likelihood of the presence of a groundwater-polluting substance, with the type of anthropogenic activity (Tables-3.1 and 3.2)
- estimating the probable hydraulic surcharge on the basis of water use in the activity concerned.

Table 3.3 Classification and ranking of diffuse pollution sources under the POSH system

SUBSURFACE CONTAMINANT LOAD POTENTIAL	POLLUTION SOURCE in-situ sanitation	agricultural practices
Elevated	mains sewer coverage less than 25 percent and population density above 100 persons/ha	intensive cash crops and most monocultures on well-drained soils in humid climates or with low-efficiency irrigation, intensive grazing on heavily fertilized meadows
Moderate	intermediate between above and below	
Reduced	mains sewer coverage more than 75 percent and population density below 50 persons/ha	traditional crop rotations, extensive pasture land, eco-farming systems, high-efficiency irrigated cropping in arid areas

Thus the approach to assessment of potentially polluting activities used in this Guide—the so-called POSH method—is based on two readily estimated characteristics: the Pollutant Origin and its Surcharge Hydraulically. The POSH method generates three qualitative levels of "potential to generate a subsurface contaminant load": reduced, moderate, and elevated (Tables-3.3 and 3.4).

3.4 Estimation of Subsurface Contaminant Load

(A) Diffuse Sources of Pollution

Urban Residential Areas without Mains Sewerage

In most towns and cities of the developing world, rapid urban population growth has resulted in large areas that are dependent upon in-situ systems (such as latrines, septic tanks and cesspits) for their sanitation (Lewis and others, 1982). Such systems function by liquid effluent percolation to the ground, and in permeable soil profiles, this results in aquifer recharge. As regards the solid fraction, it should be periodically removed and disposed off site, but in many cases it remains in the ground and is progressively leached by infiltrating rainfall and other fluids.

The types of contaminant commonly associated with in-situ sanitation are the nitrogen compounds (initially in the form of ammonium but normally oxidized to nitrate), microbiological contaminants (pathogenic bacteria, viruses, and protozoa), and in some cases community synthetic organic chemicals. Among these contaminants, nitrates will always be mobile and often be stable (and thus persistent), given that in most groundwater systems, oxidizing conditions normally prevail.

Box 3.2

Assessment of the microbiological pollution hazard in Rio Cuarto, Argentina

The evaluation of aquifer pollution vulnerability provides a framework within which to design and implement surveys of subsurface contaminant load, and to use the results for assessing groundwater pollution hazard, designing focused groundwater sampling campaigns, and through these, prioritizing remedial actions.

- The town of Rio Cuarto (Cordoba), Argentina has a population of some 140,000 who are dependent upon groundwater for all their water supply requirements. About 75 percent have access to mains water supply and the mains sewerage system has around 50 percent coverage, with the remainder utilizing directly abstracted well-water and in-situ wastewater disposal respectively.
- The town is underlaid by a largely unconfined aquifer formed in very heterogenous Quaternary sediments, and its groundwater is of good natural quality appropriate for human consumption. The GOD methodology suggests that the aquifer pollution vulnerability, however, ranges from moderate to high. Superimposing the results of a systematic sanitation survey, it was predicted that the aquifer pollution hazard varies spatially from very low to extremely high (Blasarin and others, 1993).
- With the aim of confirming the aquifer pollution hazard assessment and of establishing a strategy for managing the problem that it presented, a detailed groundwater quality study was undertaken in two districts (Quintitas Golf and Villa Dalcar), neither of which yet have mains sewerage. Some 60 percent of the samples analyzed proved to be unfit for human consumption as a result of the elevated fecal coliform counts, and in some cases both nitrate and chloride were elevated in relation to background levels (Blasarin and others, 1999).
- The co-existence of domestic water supply wells and in-situ sanitation facilities in areas of high aquifer pollution vulnerability was declared to be a public health risk, and priorities were, accordingly, recommended for the expansion of the mains water supply network and the improvement in the design of many in-situ sanitation units.

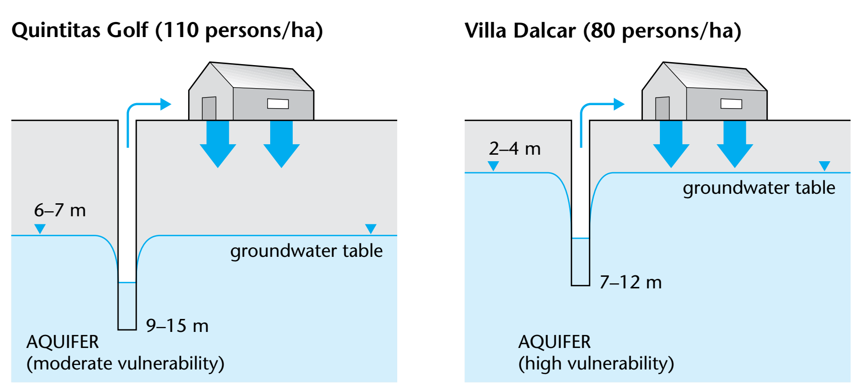
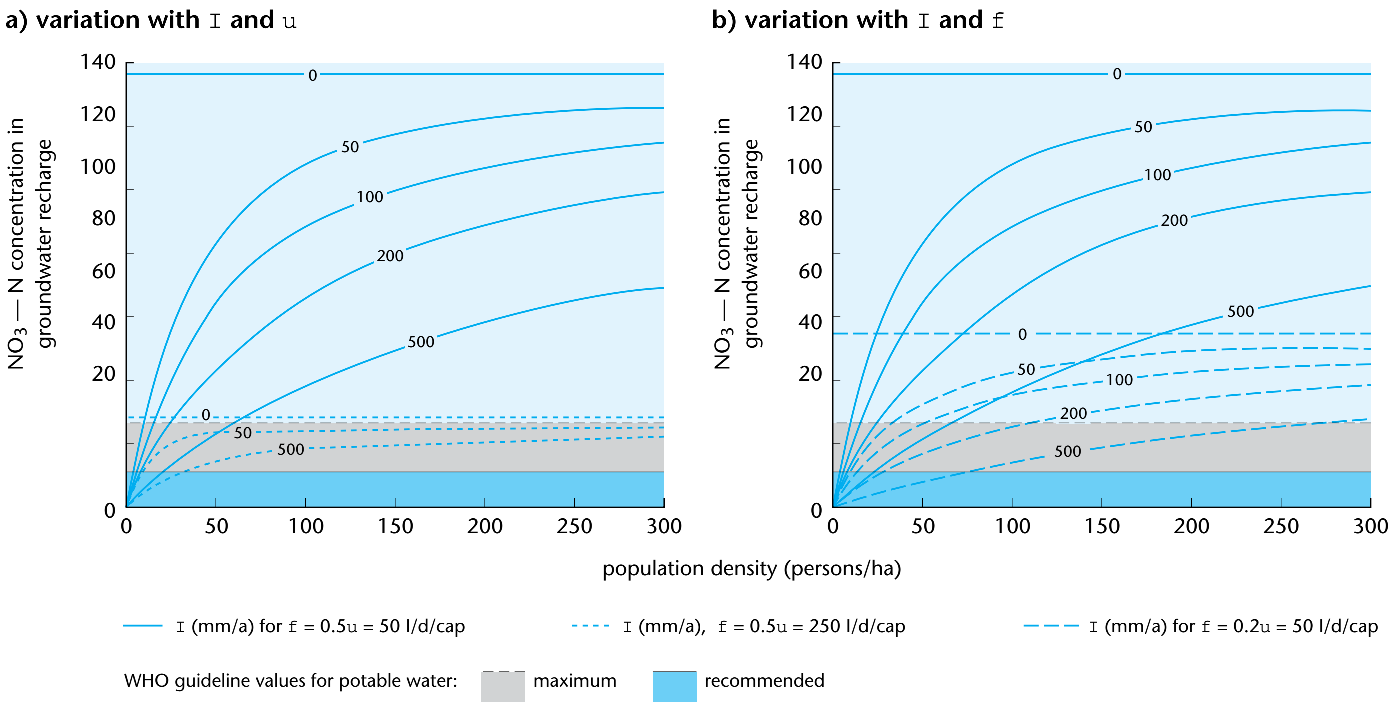


Figure 3.4 Estimation of nitrogen load in groundwater recharge of areas with in-situ sanitation



Note: Variation with population density, natural rate of rainfall infiltration (I in mm/a), and the nonconsumptive portion of total water use (u in l/d/cap) is shown; f being the proportion of excreted nitrogen leached to groundwater.

The presence of in-situ sanitation (together commonly with high rates of water mains leakage) often results in heavy hydraulic surcharging and high rates of aquifer recharge in urban areas, despite the general tendency for the land surface to be impermeabilized and rainfall infiltration to be reduced (Foster and others, 1998). Overall rates of urban recharge in developing nations are believed widely to exceed 500 mm/a. In districts where mains sewerage cover is limited or absent, and where urban population densities exceed 100 persons/ha, there exists an elevated potential subsurface contaminant load (Figure-3.4), especially where in-situ sanitation units are improperly operated and maintained. However, in predominantly residential areas with extensive coverage of mains sewerage, this potential is reduced, despite the probable existence of leakage from mains sewerage systems (which only threatens groundwater quality locally).

In many urban and periurban areas it is commonplace to find small manufacturing and service industries (including motor vehicle workshops, petrol filling stations, etc.), that often handle toxic chemicals (such as chlorinated solvents, aromatic hydrocarbons, etc.). In this case it is important to identify any areas where such activities may be discharging effluents directly and untreated to the ground (rather than to other means of disposal or recycling).

Data on population density (Table 3.3), together with the proportion of the urban area with mains sewerage cover, are generally available from municipal authorities. Moreover, in many instances municipal authorities or water service utilities have reliable information on which industries are connected to the sewerage system. However, in some cases it may be necessary to survey in the field, through direct inspection on a block-by-block basis.

Agricultural Soil Cultivation

The agricultural cultivation of soils exerts a major influence on the quality of groundwater recharge, and also with irrigated agriculture the actual overall recharge rates (Foster and Chilton, 1998; Foster and others, 2000). Some agricultural soil cultivation practices cause serious diffuse contamination, principally by nutrients (mainly nitrates) and sometimes by certain pesticides. This is especially true in areas with relatively thin, freely draining soils (Foster and others, 1982; Vrba and Romijn, 1986; Foster and others, 1995; Barbash amd Resek, 1996). However, the other major plant nutrients (potassium, phosphate) tend to be strongly retained in most soils and not heavily leached to groundwater.

It is of relevance here to note that a major U.S. national evaluation of the occurrence of pesticide compounds in groundwater (20 major catchments during 1992–96) showed:

- pesticide presence in 48 percent of the 3,000 samples collected (Kolpin and others, 2000), but in the majority of cases at concentrations below WHO potable quality guidelines
- that in the phreatic aquifers of the maize and soya bean cultivation tracts of the mid-western states, 27-pesticide compounds were detected, and of the 6 most widely detected, no fewer that 5 were herbicide metabolites (partial breakdown products)
- the presence of alachlor derivatives was especially significant, since the parent compound was not detected, implying breakdown in the soil to a more mobile and persistent derivative
- pesticide contamination was widely found in urban areas, as a result of excessive application to private gardens, recreational facilities, sports grounds, and other areas.

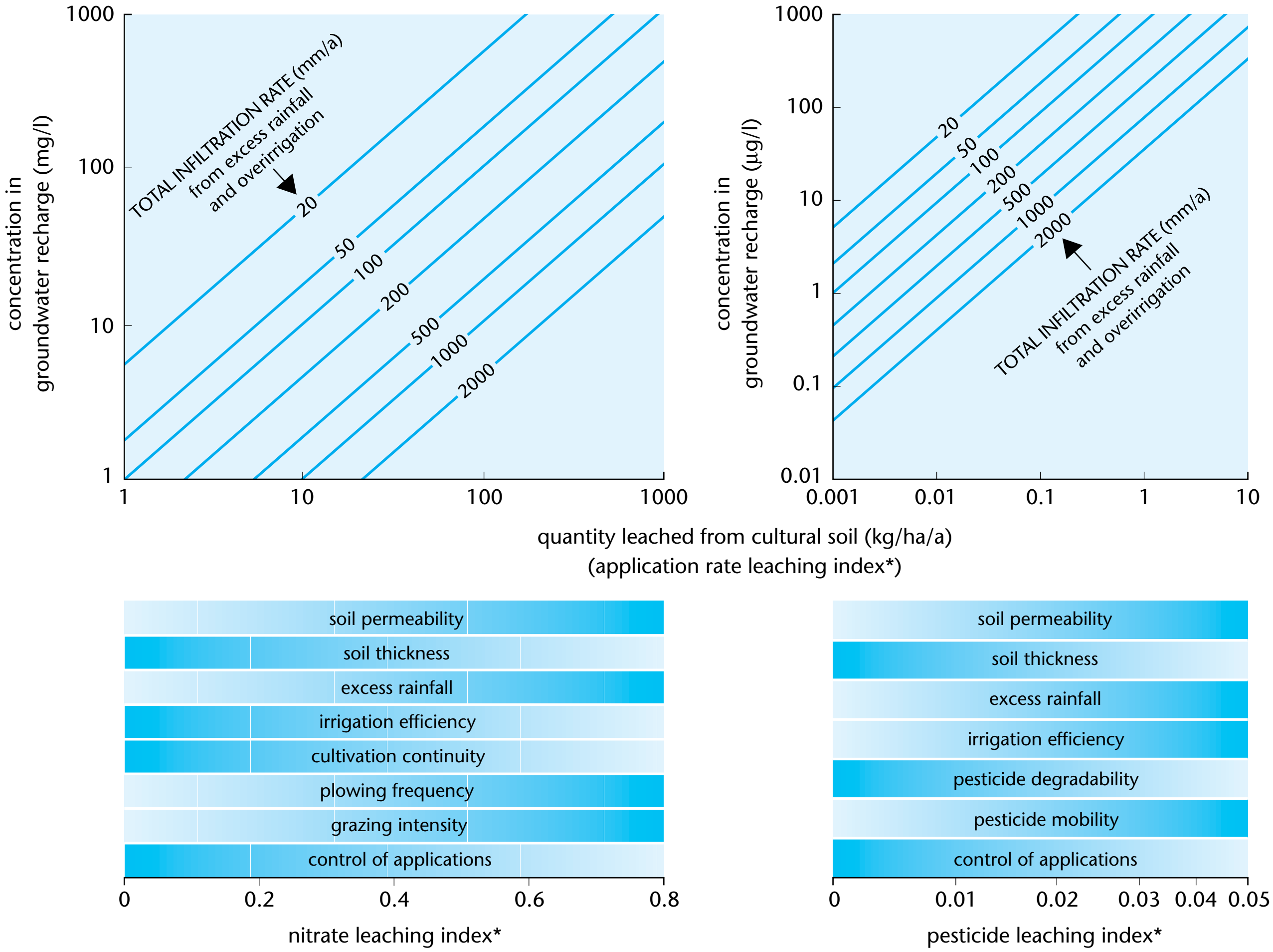
The types of agricultural activity that generate the most serious diffuse contamination of groundwater are those related to extensive areas of monoculture. More traditional crop rotations, extensive pasture land, and ecological farming systems normally present less probability of a subsurface contaminant load. Agriculture involving the cultivation of perennial crops also normally has much lower leaching losses than where seasonal cropping is practiced, because there is less disturbance and aeration of the soil and also a more continuous plant demand for nutrients. However, when perennial crops have to be renewed and the soil plowed, there can be major release and leaching of nutrients.

There normally exists some correlation between the quantity of fertilizers and pesticides applied, and their leaching rates from soils into groundwater. Nevertheless, only a proportion of agrochemicals applied are leached, and since leaching results from a complex interaction between:

- cultivation type

Figure 3.5 Estimation of potential contaminant load in groundwater recharge from cultivated land

a) nitrate (as NO3-N) **b) pesticide compounds**



- soil properties
- rainfall and irrigation regime
- management of soil and agrochemical applications,

it is difficult to provide simple methods for the estimation of leaching rates.

Moreover, only a small proportion of the nitrate leached from soils is normally derived directly from the application of fertilizers in the preceding growing season. However, fertilization levels influence the level of soil organic nitrogen; from this level nitrate is released proportionally by oxidation, especially at certain times of the year and following plowing or irrigation. Values of leaching losses obtained from the literature indicate that up to 75 percent of the total N applied can be oxidized and leached to groundwater (although values of 50 percent are more common). In the case of pesticides, leaching losses rarely reach 5 percent of total active ingredient applied and more normally are less that 1 percent (Foster and Hirata, 1988). The factors that determine the rates of soil leaching from cultivated soils within this range are summarized in Figure-3.5 (Foster and others, 1991).

Given the difficulty in making precise estimates of leaching losses, the classification of agricultural land in terms of its potential to generate subsurface contaminant load must begin by mapping the distribution of the more important crops, together with inventory of their fertilizer and pesticide applications. With these data it will usually be possible to classify the cultivated land area on the basis of likelihood that the farming activity will potentially generate a low, moderate, or elevated subsurface contaminant load.

In some instances the total amounts of agrochemicals applied to a given crop are not known with certainty. In this case reasonable approximations can often be made through consultation with agricultural extension staff on recommended application rates, assuming that farmers are making correct use of the product concerned. If this type of approach is used, it is necessary to bear in mind that farmers commonly opt for specific products according to their local market availability and commercial publicity.

If it is not possible to obtain the above information, then a further simplification can be used, based on a classification (Table 3.3) of:

- probable levels of fertilizer and/or types of pesticide use
- the hydraulic load on the soil as a result of the rainfall and/or irrigation regime.

Another frequent difficulty is the lack of reliable up-to-date information on the distribution of agricultural crop types, even where the total area planted to a given crop in any given year is known at municipality or county level. Moreover, in developing economies there are often rapid changes in agricultural land use. Often land-use maps are outdated and it is necessary to use more recent aerial photographs for such information if available. Satellite images can also be used, despite the fact that their resolution does not generally allow a close differentiation of crop types, but they have the advantage of being up-to-date and offering the possibility of studying trends in land-use change.

One other aspect has to be considered, especially in the more arid climates, and this is agricultural irrigation with wastewater. Wastewaters invariably contain nutrients and salts in excess of crop requirements, and thus leads to significant leaching losses from agricultural soils. There also exists the risk of infiltration of pathogenic micro-organisms and trace synthetic organic compounds as a result of wastewater irrigation.

Additionally, it must be kept in mind that the risk of pesticide leaching to groundwater from agricultural practices is not limited to their use at field level, since storage and use in livestock rearing can also lead to groundwater contamination, especially where such compounds are inadequately stored and/or handled.

(B) Point Sources of Pollution

Industrial Activities

Industrial activities are capable of generating serious soil pollution and major contaminant loads on the subsurface, as a result of the volume, concentration, and range of chemical products and residues that they handle. In general terms, any industrial activity is capable of generating a subsurface contaminant load as a result of the emission of liquid effluents, the inadequate disposal of solid wastes (Pankow and others, 1984; Bernardes and others, 1991), and unwanted materials, together with accidents involving leaks of hazardous chemical products (Sax, 1984). Compounds frequently detected in groundwater contamination plumes related to industrial activities usually show a close relationship with those used in the industrial activity, which in turn are directly related to the type of industry concerned (Table-3.5).

The handling and discharge of liquid effluents is one aspect of industrial activity that merits detailed attention in relation to groundwater contamination. In industries located close to surface watercourses, direct discharge of liquid industrial effluents is often practiced, and in

Table 3.4 Classification and ranking of point pollution sources under the POSH system

POTENTIAL FOR SUBSURFACE CONTAMINANT LOAD GENERATION	POLLUTION SOURCE: solid waste disposal	industrial sites*	wastewater lagoons	miscellaneous urban	mining and oil exploration
Elevated	industrial type 3 waste, waste of unknown origin	type 3 list, any activity handling >100 kg/d of hazardous chemicals	all industrial type 3, any effluent (except residential sewage) if area >5 ha		oilfield operations, metalliferous mining
Moderate	rainfall >500mm/a with residential/ industrial type 1/ agroindustrial wastes, all other cases	type 2 list	residential sewage if area >5 ha, other cases not above or below	gas filling stations, transportation routes with regular traffic of hazardous chemicals	some mining/ quarrying of inert materials
Reduced	rainfall <500mm/a with residential/ industrial type 1/ agroindustrial wastes	type 1 list	residential, mixed urban, agro-industrial, and nonmetalliferous mining wastewater if area <1 ha	cemeteries	

* contaminated land from abandoned industries should have same ranking as industry itself

List 1 Industries: woodworking, food and beverage manufacturers, sugar and alcohol distilleries, non-metallic material processing

List 2 Industries: rubber factories, paper and pulp mills, textile factories, fertilizer manufacturers, electrical factories, detergent and soap manufacturers

List 3 Industries: engineering workshops, oil/gas refineries, chemical/pharmaceutical/plastic/pesticide manufacturers, leather tanneries, electronic factories, metal processing

Table 3.5 Summary of chemical characteristics and hazard indices for common industrial activity

INDUSTRIAL TYPE	Mazurek Hazard Index (1–9)	relative water use	salinity load	nutrient load	organic load	hydrocarbons	fecal pathogens	heavy metals	synthetic organics	Groundwater Pollution Potential Index (1–3)
Iron and Steel	6	**	●	●	●●	●●	●	●●	●●	2
Metal Processing	8	*	●	●	●	●	●	●●●	●●●	3
Mechanical Engineering	5–8	*	●	●	●	●●●	●	●●●	●●	3
Nonferrous Metals	7	*	●	●	●	●	●	●●●	●	2
Nonmetallic Minerals	3–4	**	●●●	●	●	●	●	●	●	1
Petrol and Gas Refineries	7–8	*	●	●●	●●●	●●●	●	●	●●	3
Plastic Products	6–8	**	●●●	●	●●	●●	●	●	●●●	3
Rubber Products	4–6	*	●●	●	●●	●	●	●	●●	2
Organic Chemicals	3–9	**	●●	●	●●	●●●	●●	●●	●●●	3
Inorganic Chemicals	6–9	**	●●	●	●	●	●	●●●	●	.
Pharmaceutical	6–9	***	●●●	●●	●●●	●	●●	●	●●●	3
Woodwork	2–4	*	●●	●	●●	●	●	●	●●	1
Pulp and Paper	6	***	●	●●	●●	●	●	●	●●	2
Soap and Detergents	4–6	**	●●	●	●●	●●	●●	●	●	2
Textile Mills	6	***	●●	●●	●●●	●	●	●	●●	2
Leather Tanning	3–8	**	●●●	●●	●●	●	●	●●	●●●	3
Food and Beverages	2–4	**	●●	●●●	●●●	●	●●●	●	●	1
Pesticides	5–9	**	●●	●	●	●	●	●	●●●	3
Fertilizers	7–8	*	●●●	●●●	●	●●	●	●	●●	2
Sugar and Alcohol	2–4	**	●●●	●●●	●●●	●●	●	●	●	2
Thermo-Electric Power	–	***	●	●	●	●●●	●	●●●	●●	2
Electric and Electronic	5–8	*	●	●	●	●●●	●	●●	●●●	3

● low
●● moderate
●●● high
} probability of troublesome concentrations in process fluids and/or effluents

Source: Abstracted from BNA, 1975; DMAE, 1981; Hackman, 1978; Luin and Starkenburg, 1978; Nemerow, 1963 and 1971; Mazurek, 1979; US-EPA, 1977 and 1980, and WHO, 1982 and other minor unpublished reports.

other situations the disposal of effluents through soil infiltration is sometimes used. Other than in cases where the industry concerned undertakes systematic effluent treatment, such practices will always present a direct or indirect hazard to groundwater quality. Moreover, where effluent storage and treatment is undertaken in unlined lagoons, these also represent a significant groundwater pollution hazard.

The POSH classification of industrial activities in relation to their potential for generation of a subsurface contaminant load is based on (Table-3.4):

- the type of industry involved, because this controls the likelihood of certain serious groundwater contaminants being used
- the probable hydraulic surcharge associated with the industrial activity, estimated by the volume of water utilized.

In terms of the type of industry, great emphasis needs to be put on the likelihood of utilizing appreciable quantities (say more than 100-kilograms per day) of toxic or dangerous substances, such as hydrocarbons, synthetic organic solvents, heavy metals, etc. (Hirata and others, 1991, 1997). In all such cases the index of subsurface contamination potential should be elevated, since factors like chemical handling and effluent treatment cannot be considered a result of the general difficulty in obtaining reliable data.

Effluent Lagoons

Effluent lagoons are widely used in many parts of the world for the storage, treatment, evaporation, sedimentation, and oxidation of liquid effluents of industrial origin, urban wastewaters, and mining effluents. Such lagoons are generally relatively shallow (less than 5-meters deep), but their retention time can vary widely from 1–100-days.

Following the POSH classifications, the subsurface contamination potential of these installations depends on two factors:

- the likelihood of serious groundwater pollutants being present in the effluent, which is primarily a function of their industrial origin
- the rate of percolation from the lagoon into the subsoil, which is primarily a function of lagoon construction and maintenance (whether base and walls are fully impermeabilized).

In a process of rapid assessment, it is difficult to obtain reliable estimates of the total volume of effluents entering and leaving the system. But studies of unlined lagoons (still the most popular form of construction in the developing world) show that infiltration rates are often equivalent to 10–20 milligrams per day (Miller and Scalf, 1974; Geake and others, 1987). However, while it is not easy to make full hydraulic balances for lagoons, it is possible to estimate whether they are generating significant recharge to underlying aquifers on the basis of their areal extension and hydrogeological location.

In the majority of cases, it is not possible to obtain data on the quality of liquid effluents, but the likelihood of serious groundwater contaminants being present can be judged from the type of industrial or mining activity involved (Table-3.5). It must be borne in mind that many less mobile contaminants will be retained in sediments forming the lagoon bed; this is especially true of pathogenic microorganisms and heavy metals. Lagoons receiving urban wastewater generally have a heavy load of organic material and pathogenic microorganisms, together with high concentrations of nutrients and sometimes salts. If the associated sewerage system serves nonresidential areas, it is likely to contain the effluents of small-scale industries (such as mechanical workshops, dry cleaning shops, printing works, etc.), and in such cases wastewater could contain synthetic organic solvents and disinfectants.

The POSH classification approach to the assessment of the relative potential of wastewater lagoons to generate subsurface contaminant loads is given in Table-3.4, which uses easily obtained data on:

- the type of activity generating the wastewater and effluents involved
- the area occupied by the lagoon(s).

Solid Waste Disposal

The inadequate disposal of solid waste is responsible for a significant number of cases of groundwater pollution (US-EPA, 1980; Gillham and Cherry, 1989). This is more prevalent in regions of humid climate where substantial volumes of leachate are generated from many sanitary landfills and waste tips, but also occurs in more arid climates where leachates will generally be more concentrated. The subsurface contaminant load generated from a waste tip or sanitary landfill is a function of two factors:

- the probability of the existence of groundwater contaminants in the solid waste
- the generation of a hydraulic surcharge sufficient to leach such contaminants.

The type of contaminants present is principally related to the origin of the waste and to (bio)chemical reactions that occur within the waste itself and in the underlying vadose zone (Nicholson and others, 1983). Evaluation of the actual quality of leachates requires a detailed monitoring program, but can also be estimated in general terms on the basis of waste origin (urban residential, industrial, or mining) and the construction and age of the disposal facility. Calculation of the hydraulic surcharge necessitates a monthly hydraulic balance for the landfill, together with knowledge of the level of impermeabilization of its surface and base, even allowing for the fact that some leachate will be generated from the waste materials themselves. A classification of the relative potential to generate a subsurface contaminant load can be obtained by the interaction (Table 3.4) of:

- the origin of the waste, which indicates the likely presence of groundwater contaminants
- the probable hydraulic surcharge estimated from the rainfall at the waste disposal site.

In some cases the origin of the solid waste is uncertain, as a result of the absence of controls over the types of residues received. In this case, it is a wise precaution to classify the solid waste disposal activity as generating a potentially elevated subsurface contaminant load, regardless of the precipitation regime. Such a precautionary approach is not considered excessive because small volumes of toxic substances (such as synthetic organic compounds) can cause major groundwater quality deterioration (Mackey and Cherry, 1996).

Gas Stations

Gas stations are responsible for a large number of cases of groundwater contamination (Fetter, 1988), although individual incidents are not major. Such installations are widely distributed and handle major volumes of potentially polluting hydrocarbons stored in underground tanks that do not allow visual inspection for leaks. The main sources of soil and groundwater pollution are corroded tanks, and there is a strong correlation between the incidence and size of leaks and the age of installed tanks (Kostecki and Calabrese, 1989; Cheremisinoff, 1992). There is a high probability that tanks more than 20 years old are seriously corroded and subject to substantial leaks unless they receive regular maintenance. Moreover, pipe work between tanks and delivery systems can become ruptured due to the traffic of heavy vehicles or due to initial poor quality installation.

Most gas stations measure hydrocarbon fuel levels at the beginning and end of every working day as a matter of routine, normally through electric level-measuring systems. These figures are compared to the volumes sold, as measured by discharge gauges. However, such measurements do not necessarily give a clear idea of subsurface leakage from tanks, because they are not especially sensitive, and relatively small losses can cause significant groundwater contamination plumes as a result of the high toxicity of the substances concerned. Regular standardized tests of tank integrity are a far better measure of the likely losses of hydrocarbon fuels. Losses due to tank corrosion can be significantly reduced if higher design, construction, operation, and maintenance standards are applied. In particular the use of steel or plastic tanks reinforced with glass fibers or double-walled tanks offer much greater security against leakage, and cathodic protection greatly reduces corrosion.

Taking into account the small areas generally affected and the strong natural attenuation of hydrocarbon compounds, the presence of gas stations and storage facilities with underground storage tanks should be interpreted as a subsurface contaminant load source of moderate intensity, unless high design standards and regular maintenance are evident. An additional hazard will exist where gas stations are combined with auto repair shops that use large quantities of synthetic organic solvents and hydrocarbon lubricants, because these may be discharged to the soil without controls.

Mining Activities and Hydrocarbon Exploitation

Mining and hydrocarbon exploitation activities can cause important impacts on groundwater quality as a result of:

- hydraulic modifications to groundwater flow systems, either directly or indirectly, as a result of the construction and operation of both open-cast and subsurface excavations
- increase in the pollution vulnerability of aquifers, as a result of the physical removal of

parts of the vadose zone or confining beds that provided natural protection

- disposal of mine drainage waters or saline hydrocarbon reservoir fluids, by land spreading, discharge to surfacewater courses, or in evaporation lagoons subject to percolation
- infiltration of leachate from mine spoil heaps
- disposal of solid wastes and liquid effluents in abandoned mine excavations
- operation of subsurface mines or oil wells when they are located immediately below important water supply aquifers
- mobilization of heavy metals and other compounds due to changes in groundwater flow regime in mined areas and associated changes in hydrochemical conditions.

As a result of the great complexity of these activities and the hydraulic changes they provoke, it is necessary to analyze them on an individual basis to assess their potential impact on groundwater quality. Thus no rapid assessment method can be recommended. However, at the preliminary evaluation level, it is possible to differentiate three principal groups of extractive industries, each of which have significantly different requirements in terms of evaluating the groundwater pollution hazard that they pose:

- quarrying of inert materials, such as those used for civil engineering construction where the principal concern is assessing the changes that mining activity may have caused to pollution vulnerability of underlying aquifers and their groundwater flow system
- mining of metals and other potentially reactive deposits, where more attention needs to be paid to the handling of mining spoils, which in many cases can contain potential groundwater contaminants (such as heavy metals and arsenic), and the disposal of mine drainage waters that can be highly contaminating if not properly handled
- hydrocarbon fuel exploitation, where large volumes of saline formation water and other fluids are extracted during well drilling and operation, and—depending on their handling and disposal—can represent a major hazard for shallow aquifers in the areas concerned.

Contaminated Land

All major urban and mining areas have experienced historic changes in land use, and the closure of industrial and mining enterprises is a common occurrence especially in developing economies. The land abandoned by such enterprises can have high levels of contamination and can generate a significant subsurface contaminant load through leaching by excess rainfall. The existence of contaminated land not only poses a threat to underlying groundwater systems, but is also a health and environment hazard to those now using the land concerned. However, this latter topic is outside the scope of the current Guide.

Changes in land ownership and/or use can result in difficulties in obtaining detailed information on earlier activities and likely types/ levels of contamination arising. Old maps and aerial photographs are an important source of information in this respect, and the information they provide can sometimes be substantiated from local government archives.

The classification and evaluation of contaminated land in terms of its likelihood to generate a subsurface contaminant load to underlying aquifers requires that the historical use be established. From the type of industrial or mining activity it is possible to predict in general terms the probable occurrence and type of land contamination likely to be present. In some instances whole districts have been dedicated historically to a given type of industrial activity, and in this situation it is probably simpler to deal with the entire land area rather than attempt to work on a site-by-site basis.

The issue of responsibility for any remaining groundwater pollution risk will also arise. This may be difficult to resolve where the associated contamination could have occurred at any moment during a long time interval, perhaps before the existence of legislation to control discharges to the soil.

Polluted Surface Watercourses

A relatively common situation is the presence of contaminated (permanent or intermittent) surface watercourses crossing an area under study for groundwater pollution hazard assessment. Such watercourses will often present a major contamination hazard to underlying groundwater, and generate a significant subsurface contaminant load.

Two main factors will determine the potential for groundwater contamination:

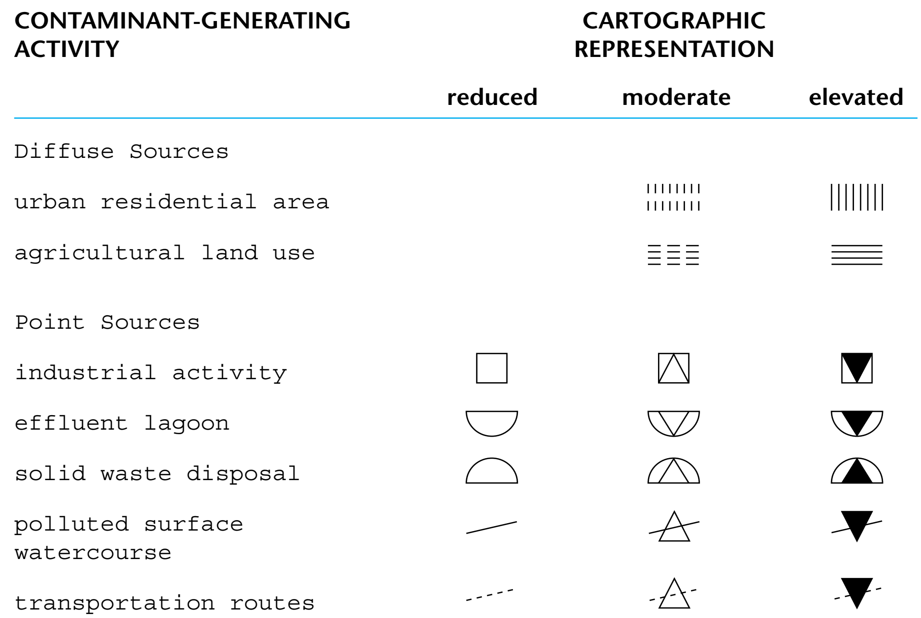
- whether the surface watercourse exhibits a loosing (influent) or gaining (effluent) behavior with respect to the underlying aquifer; the main hazard arises in relation to the former condition, but it should be noted that groundwater pumping for water supply purposes can reverse the watercourse condition from effluent to influent
- the quality of water infiltrating through the bed of surface watercourses can be greatly improved as a result of the natural pollutant attenuation during this process; however, more mobile and persistent contaminants are unlikely to be removed and will form the most important components of the associated subsurface contaminant load.

It is not easy to establish reliably the rate and quality of water infiltrating from surface watercourses without detailed investigation and sampling. But from a general knowledge of the types of contamination present and the hydrogeological setting, it should normally be feasible to establish the relative severity of the subsurface contaminant load.

Transportation Routes

Accidents involving the transport of hazardous substances occur intermittently, and the handling and disposal of any such substances following these accidents is capable of causing a significant subsurface contaminant load and threatening groundwater quality

Figure 3.6 Legend for mapping of subsurface contaminant load



in some aquifers. A similar situation occurs at major transportation terminals where these substances are regularly handled and sometimes accidentally discharged.

It is necessary to locate the major terminals and important routes, and consider the probability of them generating a subsurface contaminant load. This is by no means straightforward, but there may be statistics available on the occurrence of accidents and the frequency of transport of substances posing major hazards to groundwater, together with the types of emergency procedure normally adopted. In general terms these locations must be treated as potential sources of a contaminant load of moderate intensity, unless it is clear that there are special provisions within routine operational procedures to reduce the incidence of spillages and to avoid groundwater contamination should they occur.

Cemeteries

The burial of human remains and (in some cases animal corpses) is a relatively common practice in many cultures around the world. The question is thus sometimes asked as to whether cemeteries represent significant potential sources of groundwater contamination. Generally, this type of practice generates only a relatively small microbiological contaminant load over a restricted area, and this will be further reduced if special waterproofing of tombs and/or corrosion-resistant coffins are used. The same may not be true when large numbers of animal corpses have to be disposed of rapidly following a disease outbreak, since rapidly excavated pits might be used without special precaution or evaluation

The POSH method for the inventory of subsurface contaminant load permits an assessment of potential pollution sources into three levels: reduced, moderate, and elevated. The approach to classifying contaminant loads (and from them to groundwater pollution hazard assessment) presented here is very useful in relation to the prioritization of groundwater quality monitoring programs and of environmental inspection of field installations.

3.5 Presentation of Results

The data on potential point sources of pollution can readily be represented on maps of the same scale as those used for mapping aquifer pollution vulnerability and delineating groundwater supply protection areas. This will allow ready consideration of the interaction of the data they contain and facilitate the assessment of aquifer or source contamination hazard (see Technical Guide Part B4), but it is important that each activity is also identified by a code and registered in a database. For disperse and multi-point sources, it is generally more practical to define the land areas occupied and thus generate a potential subsurface contaminant load map, using different shading to represent the relative load intensity. A convenient legend for all such maps is presented in Figure 3.6 (Foster and Hirata, 1988). It is possible that more detailed mapping scales will be required in densely populated urban situations with a wide range of industrial and other activity.

In developing nations, land use by anthropogenic activities shows relatively rapid change, and this complicates the production of subsurface contaminant load maps. However, major advances in computing and improved facilities for color printing will increasingly make it possible for subsurface contaminant load maps to be regularly updated and printed. GIS systems are very useful in this respect, since they also allow the electronic correlation and rapid manipulation of spatial data, as well as the generation of colored images and analog maps of different attributes. Another great advantage of holding the relevant information in digital databases and maps is that they can be made available via a website and accessed by all land and water stakeholders.

This introduction to the POSH method and classification is intended to provide general orientation for the user, but it is important that it is adapted to local realities and requirements of a given groundwater pollution hazard assessment project.

B4

Assessment and Control of Groundwater Pollution Hazards

Groundwater pollution hazard can be defined as the probability that an aquifer will experience negative impacts from a given anthropogenic activity to such a level that its groundwater would become unacceptable for human consumption, according to the WHO guideline values for potable water quality. This chapter deals with its assessment and control on a practical and prioritized basis.

4.1 Evaluation of Aquifer Pollution Hazard

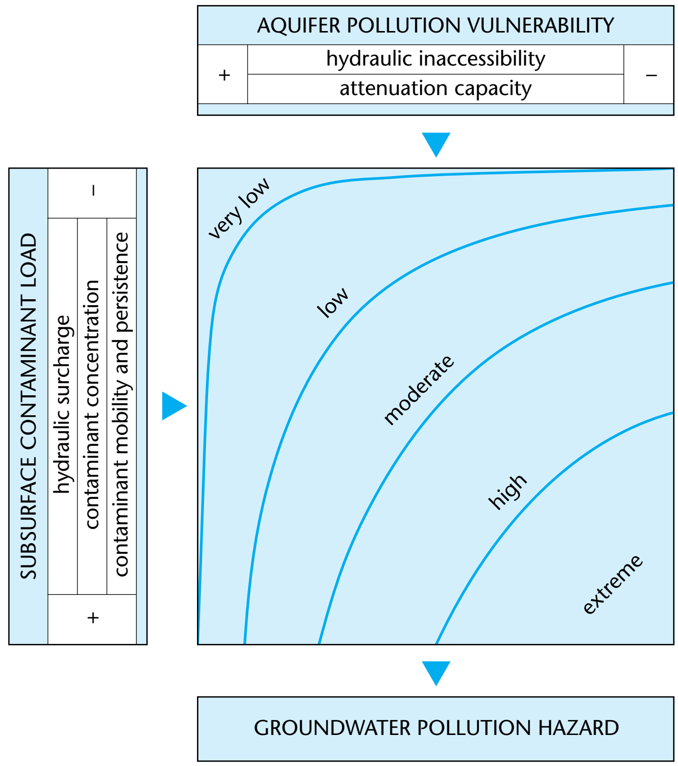
(A) Recommended Approach

The aquifer pollution hazard at any given location (Figure 4.1) can be determined by considering the interaction between:

- the subsurface contaminant load that is, will be, or might be applied on the subsoil as a result of human activities
- the vulnerability of the aquifer to pollution, which depends upon the natural characteristics of the strata that separate it from the land surface.

In practical terms, hazard assessment thus involves consideration of this interaction (Foster, 1987) through superimposition of the outputs from the subsurface contaminant load inventory (as described in Chapter 3) on the aquifer pollution vulnerability map (as specified in Chapter 1). The most serious concern will arise where activities capable of generating an elevated contaminant load are present, or are projected, in an area of high or extreme aquifer vulnerability.

Figure 4.1 Conceptual scheme for groundwater resource hazard assessment



The assessment of aquifer pollution hazards is an essential prerequisite for groundwater resource protection, since it identifies those human activities that have the highest probability of negative impacts on the aquifer and thus indicates prioritization for the necessary control and mitigation measures.

(B) Distinction between Hazard and Risk

The use of the term "groundwater pollution hazard" in this publication has exactly the same meaning as the term "groundwater pollution risk" in Foster and Hirata (1988). The change in terminology is necessary to conform with that now used for other areas of risk assessment to human or animal health and ecosystems, where risk is now defined as the product of "hazard times scale of impact." The scope of the current Guide is restricted (in this terminology) to assessing groundwater pollution hazards and does not consider potential impacts on the human population or the aquatic ecosystems dependent upon the aquifer, nor for that matter the economic value of aquifer resources.

4.2 Evaluation of Groundwater Supply Pollution Hazard

(A) Approach to Incorporation of Supply Capture Zones

The hazard concept can be extended beyond evaluation of aquifers as a whole to specific supply sources, through projection of groundwater capture zones (as delineated in Chapter

2) onto aquifer pollution vulnerability maps (Figure 4.2) (Hirata and Rebouças, 1999), prior to superimposing the outputs from the subsurface contaminant load inventory. If activities having potential to generate an elevated subsurface pollution load occur in an area of high aquifer vulnerability which is also within a groundwater supply capture zone, there will be a serious hazard of causing significant pollution of the water supply source.

For complex or unstable groundwater flow regimes, the delineation of capture zones (protection perimeters) can be fraught with problems and only limited application is feasible. In such situations aquifer pollution vulnerability mapping will have to assume the primary role in assessing groundwater pollution hazards to individual water supply sources while accepting the substantial uncertainty over the precise extension of their capture areas.

(B) Complementary Wellhead Sanitary Surveys

As a complement to the above methodology, it is strongly recommended that systematic wellhead sanitary surveys are also carried out. A standardized procedure for such surveys, leading to an assessment of microbiological pollution hazard for groundwater supplies, has been developed (Lloyd and Helmer, 1991). The survey is normally restricted to an area of 200–500 m radius (Figure 2.2), and involves scoring a series of factors through direct visual inspection and using regular monitoring of fecal coliform counts in the groundwater supply for confirmation (Table 4.1). This approach can also be readily applied in the case of domestic supplies using tubewells or dug-wells equipped with hand-pumps or using gravity-fed springs, whose abstraction rates are very small and make the delineation of capture zones impracticable.

4.3 Strategies for Control of Groundwater Pollution

Aquifer pollution vulnerability should be conceived interactively with the contaminant load that is (will be, or might be) applied on the subsurface environment as a result of human activity, thereby causing a groundwater pollution hazard. Since contaminant load can be controlled, groundwater protection policy should focus on achieving such control as is necessary in relation to the aquifer vulnerability (or, in other words, to the natural pollution attenuation capacity of the overlying strata).

(A) Preventing Future Pollution

Where land-use planning is normally undertaken, for example in relation to the expansion of an urban area or to the relocation of an industrial area, aquifer pollution vulnerability maps are a valuable tool to reduce the risk of creating future groundwater pollution hazards. They identify the areas most vulnerable to groundwater pollution, such that the location of potentially hazardous activities can be avoided or prohibited.

If the area concerned already has important groundwater supplies, source protection zones (perimeters) for these sources should be established as part of the planning process, with the

Figure 4.2 Summary of overall approach to groundwater quality protection

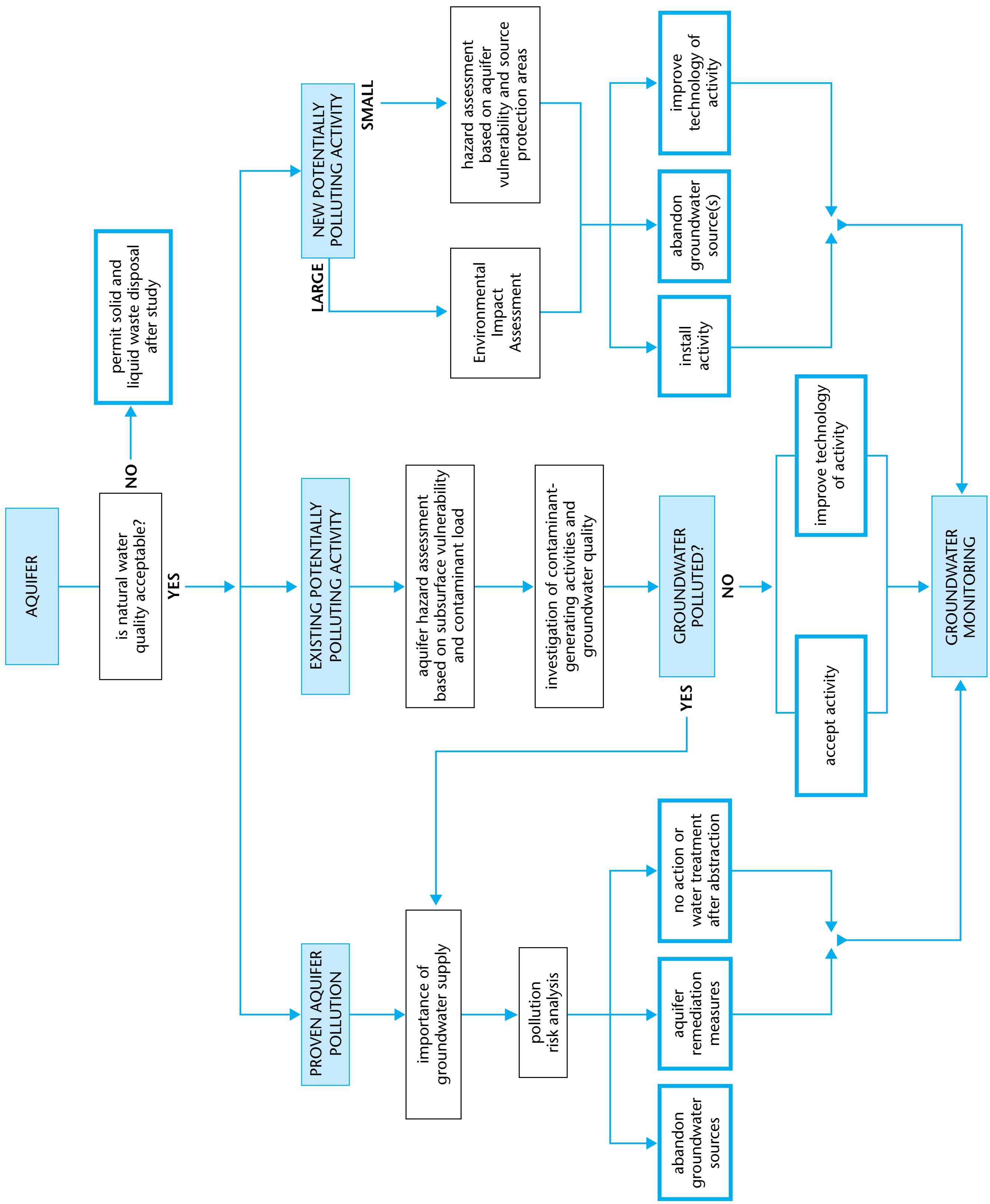


Table 4.1 Ranking system for assessing and confirming fecal pollution hazard for groundwater sources*

FACTORS IN SANITARY SURVEY		SCORE (present = 1 absent = 0)
Environmental Hazards (off-site) ● local caves, sink holes, or abandoned boreholes used for drainage ● fissures in strata overlaying water-bearing formations ● nearby sewers, pit latrines, cesspools, or septic tanks ● nearby agricultural wastes discharged or spilled Construction Hazards (on-site) ● well-casing leaking or not penetrated or sealed to sufficient depth ● well-casing not extended above ground or floor of pump room ● leaks in system under vacuum ● wellhead pump, suction pipes, or valve boxes vulnerable to flooding		cumulative score of 5–6 indicates high (and 7–8 very high) potential pollution hazard
FC RAW WATER COUNTS (mpn or cfu/100ml)	**CONFIRMED POLLUTION RISK**	
0	none	
1–10	low	
11–50	intermediate-to-high	
50–1000	high	
>1000	very high	

Source: Modified from Lloyd and Helmer, 1991

aquifer pollution vulnerability map being used to guide the levels of control of potentially polluting activity required (Table 4.2). Such an approach ought to be applied flexibly with each case analyzed specifically on its merits, taking into account the likely future level of water demand on the aquifer and the cost of alternative sources of water supply.

In the case of new potentially polluting activities of large scale and potential impact, the requirement for an Environmental Impact Assessment (EIA) as part of the authorization process is now an accepted technical and/or legal practice in many countries. Experience has shown that this mechanism ensures better consideration of environmental impacts (including those on groundwater quality) at the planning phase, facilitating a more effective approach to environmental protection. EIAs focus (Figure 4.3) on the definition and analysis of problems, conflicts, and limitations related to project implementation, including the impact on neighboring activities, the local population, and the adjacent environment (UNEP, 1988), and in certain instances may lead to project relocation at a more acceptable location. The EIA is an integral part of the feasibility study for the project concerned and

Table 4.2 Acceptability matrix of common potentially polluting activities and installations according to land surface zones for groundwater protection

POTENTIALLY POLLUTING ACTIVITY REQUIRING CONTROL MEASURES	(A) BY AQUIFER VULNERABILITY high	medium	low
Septic Tank, Cesspits and Latrines			
individual properties	A	A	A
communal properties, public	A	A	A
gasoline station	PA	A	A
Solid Waste Disposal Facilities			
municipal domestic	PN	PA	A
construction/inert	A	A	A
industrial hazardous	N	N	PA
industrial (class I)	PN	PA	A
industrial (class II and III)	N	N	PA
cemetery	PA	A	A
incinerator	N	PN	PA
Mineral and Oil Extraction			
construction material (inert)	PA	PA	A
others, including petroleum and gas	N	PA	A
fuel lines	N	PA	A
Industrial Premises			
type I	PA	PA	A
type II and III	PN/N	PA/N	PA/PN
Military Facilities	PN	PA	PA
Infiltration Lagoons			
municipal/cooling water	A	A	A
industrial effluent	PN	PA	PA
Soakaway Drainage			
building roof	A	A	A
major road	PN	PA	A
minor road	PA	A	A
amenity areas	A	A	A
parking lots	PA	A	A
industrial sites	PN*	PA	A
airport/railway station	PN	PA	A
Effluent Land Application			
food industry	PA	A	A
all other industries	PN	PA	A
sewage effluent	PA	A	A
sewage sludge	PA	A	A
farmyard slurry	A	A	A
Intensive Livestock Rearing			
effluent lagoon	PA	A	A
farmyard and feedlot drainage	PA	A	A
Agricultural Areas			
with pesticide	PN	A	A
with uncontrolled use of fertilizers	PN	A	A
pesticide storage	PN	PA	A

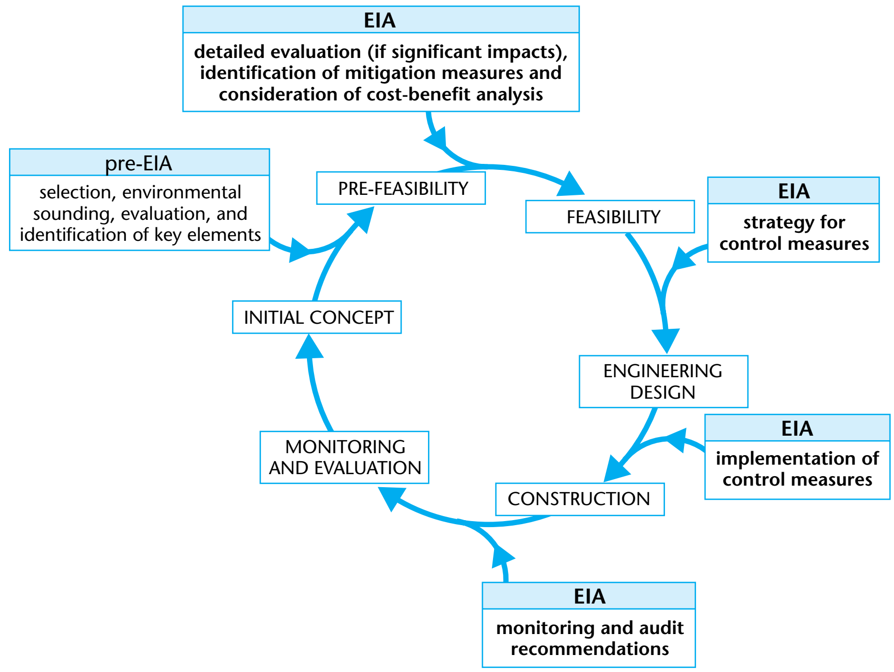
Table 4.2 continued

POTENTIALLY POLLUTING ACTIVITY REQUIRING CONTROL MEASURES	(B) BY SOURCE PROTECTION AREA I	II	III	IV
Septic Tanks, Cesspits and Latrines				
individual properties	N	N	A	A
communal properties, public	N	N	PA	A
gasoline station	N	N	PN	PA
Solid Waste Disposal Facilities				
municipal domestic	N	N	N	PN
construction/inert	N	N	PA	PA
industrial hazardous	N	N	N	N
industrial (class I)	N	N	N	PN
industrial (class II and III)	N	N	N	N
cemetery	N	N	PN	A
incinerator	N	N	N	PN
Mineral Extraction				
construction material (inert)	N	N	PN	PA
others, including petroleum and gas	N	N	N	N
fuel lines	N	N	N	PN
Industrial Premises				
type I	N	N	PN	PA
type II and III	N	N	N	N
Military Facilities	N	N	N	N
Infiltration Lagoons				
municipal/cooling water	N	N	PA	A
industrial effluent	N	N	N	N
Soakaway Drainage				
building roof	PA	A	A	A
major road	N	N	N	PN
minor road	N	PN	PA	PA
amenity areas	N	PA	PA	A
parking lots	N	N	PN	PA
industrial sites	N	N	N	PN
airport/railway station	N	N	N	PN

N = unacceptable in virtually all cases; PN = probably unacceptable, except in some cases subject to detailed investigation and special design; PA = probably acceptable subject to specific investigation and design; A = acceptable subject to standard design
I = operational zone; II = microbiological zone; III = intermediate zone; IV = entire capture area.

Source: Modified from Foster and others, 1993; Hirata, 1993.

Figure 4.3 Typical project implementation cycle with anticipated intervention of an Environmental Impact Assessment



groundwater considerations must assume particular importance where certain types of industrial production, major landfills for solid waste disposal, mining enterprises, large-scale intensive irrigated agriculture, etc., are involved.

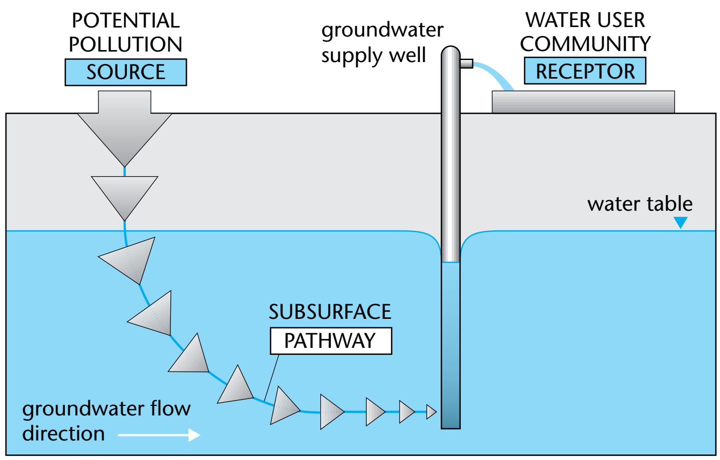
There are various distinct approaches to undertaking an EIA (Weitzenfeld, 1990), but the need to identify the capacity of the surrounding land to attenuate potential contaminant loads and the identification of groundwater supplies that might be impacted are critical, because many activities (by design or by accident) lead to effluent discharge to the soil. Thus the aquifer pollution vulnerability map and delineation of water supply source flow-time and capture areas are both key inputs, and fit into the classical EIA evaluation scheme of (potential pollution) source–pathway–receptor (Figure 4.4).

Trying to eliminate the possibility of effluent discharge can be very costly and sometimes unnecessary. Thus one of the best ways to obtain economic advantage and reduce environmental pollution hazard is to ensure that the proposed land use is fully compatible with its capacity to attenuate possible contaminants.

(B) Dealing with Existing Pollution Sources

The most frequent need will be to prioritize groundwater pollution control measures in areas where a range of potentially polluting activities are already in existence. Both in urban and rural settings it will first be necessary to establish which among these activities poses the more serious hazard to groundwater quality. The same three components (aquifer

Figure 4.4 Conceptual EIA evaluation scheme of (potential pollution) source–pathway–receptor



vulnerability mapping, delineation of water supply protection areas, and inventory of subsurface contaminant load) form the fundamental basis for such an assessment (Figure 4.5).

Table 4.3 should help in the selection of those activities that need significant attention, according to their location by aquifer vulnerability class and their position with respect

Figure 4.5 Priority groundwater pollution control action-levels based on aquifer vulnerability, source protection areas, and potential contaminant load

POTENTIAL CONTAMINANT LOAD	AQUIFER POLLUTION VULNERABILITY ZONES *			GROUNDWATER SOURCE PROTECTION AREAS	
	low	medium	high	500-day	50-day
reduced	3	3	2	2	1
moderate	2	2	1	1	1
elevated	2	1	1	1	1

ACTION-LEVEL
1 = high 2 = intermediate 3 = low

* Numbers of zones/areas reduced to simplify presentation.

Table 4.3 Examples of methods for control of potential sources of groundwater contamination

SOURCE OF POLLUTION	POSSIBLE RESTRICTIONS	ALTERNATIVES
Fertilizers and Pesticides	nutrient and pesticide management to meet crop needs; control of rate and timing of application; bans on use of selected pesticides; regulation of disposal of used containers	none
In Situ Sanitation (latrines, cesspits, septic tanks)	choose septic tanks if water use high apply septic tank design standards	mains sewerage
Underground Storage Tanks/Pipelines	double lining	install above ground leak detection
Solid Waste Disposal domestic domestic and industrial	 impermeabilization of both base and surface leachate collection and recycling/treatment monitor impact	 remote disposal
Effluent Lagoons agricultural municipal industrial	 impermeabilization of base impermeabilization of base monitor impact	 none treatment plant remote disposal
Cemeteries	impermeabilization of tombs superficial drainage	crematoria
Wastewater Injection Wells	investigation and monitor apply strict design standards	treatment remote disposal
Mine Drainage and Wastetips	operational control monitor impact	treatment (pH correction)

Source: Modified from Foster and others, 1993; Zaporozec and Miller, 2000

to source protection zones. In many cases it should be possible to reduce or eliminate subsurface contaminant load with modified design. For example, in-situ sanitation might be replaced by mains sewerage, effluent evaporation/percolation lagoons could be replaced by closed effluent treatment processes, and even a traditional cemetery might be replaced by a crematorium.

It must be recognized, however, that controls on polluting activities aimed at reducing future subsurface contaminant load will not eliminate contaminants that are already in the subsurface as a result of past practices. For example, the installation of mains sewerage in an urban district will radically reduce the existing subsurface contaminant load from in-situ sanitation, but various tons of contaminants deposited in the subsoil over previous decades may still be capable of liberating a significant contaminant load to an underlying aquifer.

In some instances and at certain locations, it may be possible to accept a potentially polluting activity without any alteration to its existing design, subject to the implementation of an offensive campaign of groundwater quality monitoring. This would require the installation of a monitoring network (capable of detecting any incipient groundwater contamination and of giving "early warning" of the need to take remedial action) in the immediate proximity of the activity concerned (Section 4.4B).

(C) Approach to Historic Land Contamination

Significant tracts of urban land and more isolated rural sites that have experienced extended periods of occupancy by certain types of industrial, mining, or military activity often exhibit serious contamination, even where the corresponding activity was shut down years previously. This contaminated land can generate a serious pollution load to groundwater under certain circumstances. In such cases it is necessary to evaluate the risk in terms of probability of impacts on humans, animals, and plants, resulting from contact with and/or ingestion of the contaminated land and/or groundwater.

This type of risk assessment, which is normally used to guide the decision on priorities for remedial or clean-up measures, is not dealt with in detail here and those requiring further detail are referred to ASTM (1995). Such risk assessments often use the following criteria (Busmaster and Lear, 1991):

- where there is 95 percent probability of health impacts on a 1-in-10,000 basis, then immediate remediation works are essential
- where the corresponding value is between 1-in-10,000 and 1-in-1,000,000, more detailed cost-benefit studies and uncertainty evaluation are recommended
- below the latter level no action is generally taken.

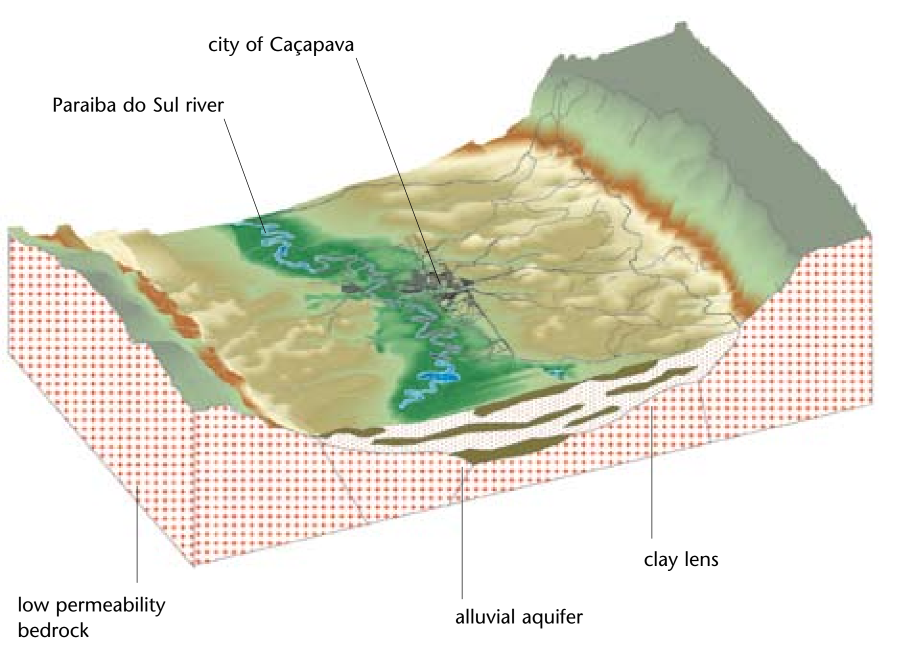
(D) Selecting New Groundwater Supply Areas

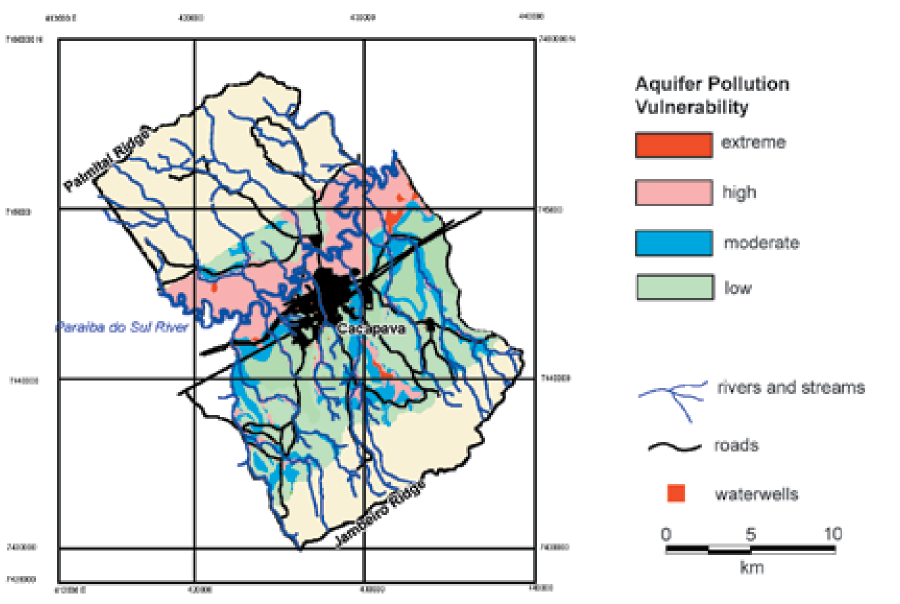
The selection of areas in which to site new municipal groundwater supply sources should involve the same procedure as recommended above for assessing the pollution hazard to existing groundwater supplies. In situations where such an assessment identifies anthropogenic activities capable of generating an elevated subsurface contaminant load and/or the aquifer pollution vulnerability is high or extreme over most of the designated groundwater supply capture area, this assessment should be followed by a technical and economic appraisal to establish whether:

- it will be possible to control adequately all relevant potential pollution sources
- it would be advisable to look for other sites for the new groundwater supply sources.

Box 4.1

Use of GIS techniques in groundwater pollution hazard assessment in the Caçapava area of Brazil





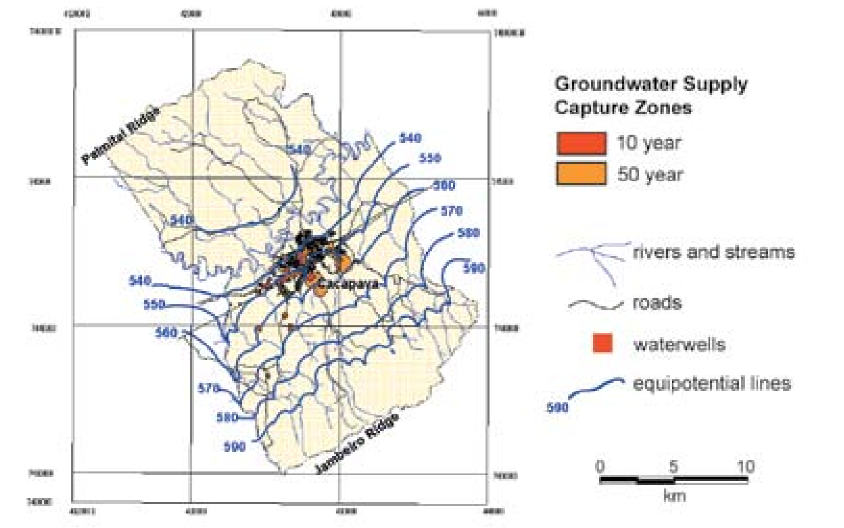
The utilization of GIS (Geographical Information System) techniques for data management is especially appropriate in the work of groundwater pollution hazard assessment and control. They facilitate efficient data storage, up-dates, manipulation, and integration. Moreover, they allow the flexible presentation of results, for both environment sector professionals and stakeholders, in a variety of interactive and paper outputs.

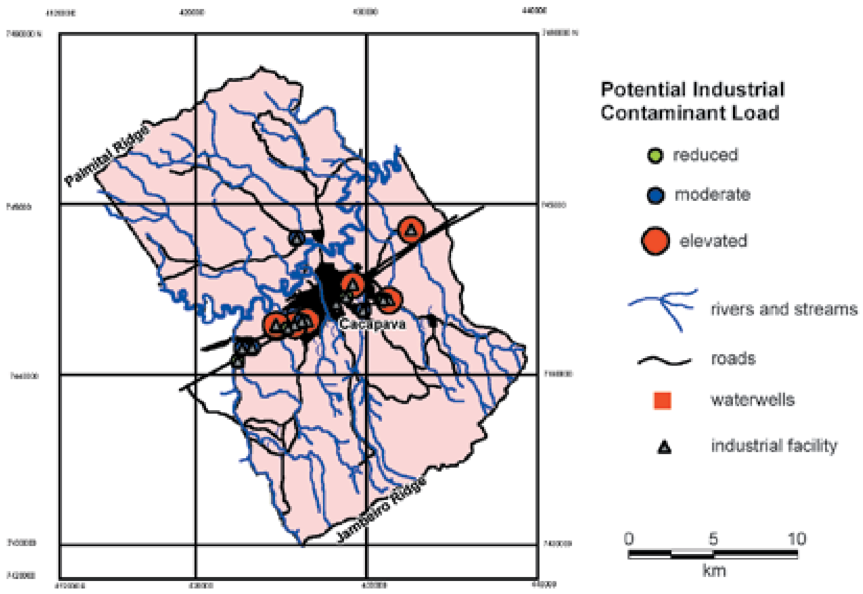
- The town of Caçapava (Sao Paulo) in Brazil is highly dependent upon groundwater resources. The alluvial aquifer under exploitation consists of sand and gravel deposits with interbedded clay horizons, reaching in total a thickness of 200–250 m. Its groundwater is mainly unconfined, except locally where it becomes semi-confined by clay lenses.

- In the past, it has suffered significant financial losses as a result of a number of cases of aquifer contamination, which manifested the need for a systematic approach to groundwater pollution hazard assessment and a rational strategy for prioritizing pollution control measures. The mapping of aquifer pollution vulnerability by the GOD method was one of the first steps in its groundwater protection program. A GIS was used to put into a database the spatial variation of the factors entering into the GOD methodology (Martin and others, 1998).

- The next step was to delineate the protection perimeters (and thus capture zones) of the principal municipal water supply boreholes corresponding to 10 and 50 years saturated zone travel time. This was done using a numerical 3-D groundwater flow model generating a GIS-compatible output to facilitate their geographical superimposition on the vulnerability map.

- A survey and inventory of potential pollution sources (mainly industrial premises and gas stations) was then carried out. Application of the POSH approach to assessment led to their ranking as elevated, moderate, or reduced potential to generate a significant subsurface contaminant load. These results were also incorporated in the GIS to highlight locations for priority action or special vigilance in the interests of protecting the existing sources of potable water supply.





4.4 Role and Approach to Groundwater Quality Monitoring

An additional and essential component of groundwater protection programs is aquifer water level and quality monitoring (Figure 4.2). This is needed to:

- understand the baseline natural quality of the groundwater system
- collect new data on the aquifer system to improve its conceptual and numerical modelling
- provide verification of groundwater pollution hazard assessments
- confirm the effectiveness of groundwater quality protection measures

This monitoring need is distinct from that required for direct analytical surveillance of the quality of water (from waterwells and springs) destined for public supply.

The representativity and reliability of aquifer groundwater quality monitoring is very much a function of the type and number of monitoring installations in place. The cost of borehole drilling as such often exercises a severe constraint on the number of monitoring installations (except in situations of a shallow water table) and exerts a strong pressure to make recourse to production wells for aquifer monitoring.

(A) Limitations of Production Well Sampling

Most production wells have their groundwater intake over a large depth range, so as to maximize their yield-drawdown performance. They thus tend to pump a "cocktail of groundwater" of widely different

- origin, in terms of recharge area and date (in many cases mixing groundwater with residence times ranging over decades, centuries, or even millenia)
- hydrogeochemical evolution, in terms of modification through aquifer-water interaction and natural contaminant attenuation.

This will inevitably exert a serious limitation on the extent to which such monitoring data can be interpreted and extrapolated in many types of aquifer system (Foster and Gomes, 1989).

Moreover, production well sampling is usually undertaken via a wellhead tap during routine operation of a high-capacity pumping plant. Thus another factor complicating the interpretation of this type of groundwater quality data is possible physiochemical modification of groundwater samples (compared to the in-situ condition) due to such processes as:

- air entry from borehole pumps (or other sampling devices) causing oxidation, and precipitation-dissolved metal ions and other constituents sensitive to changes in Eh
- volatilization, causing loss of unstable compounds such as petroleum hydrocarbons and synthetic organic solvents
- depressurization, causing loss of dissolved gases such as CO_2 and modifying pH.

Such limitations are, all too often, not taken into account when interpreting the data provided by routine water quality surveillance in production waterwells for groundwater resource management and protection purposes. Fuller technical details of these limitations, and approaches to reducing sampling bias, can be found in Foster and Gomes (1989).

(B) Systematic Monitoring for Groundwater Pollution Control

Purpose-drilled, intelligently sited, and carefully constructed monitoring boreholes (or piezometers) are the most accurate means of obtaining groundwater samples representative of in-situ conditions in an aquifer system. These comprise small-diameter boreholes (50 millimeters or even less) with short screen lengths (2–5 meters), completed with relatively inert materials (stainless steel, teflon, or pvc). Appropriate drilling and installation procedures (including a bentonite seal to prevent cross-contamination via the borehole annulus) are required, but these are usually available in most countries (Foster and Gomes, 1989).

Three distinct strategies can be adopted in systematic monitoring for groundwater pollution protection (Figure 4.6):

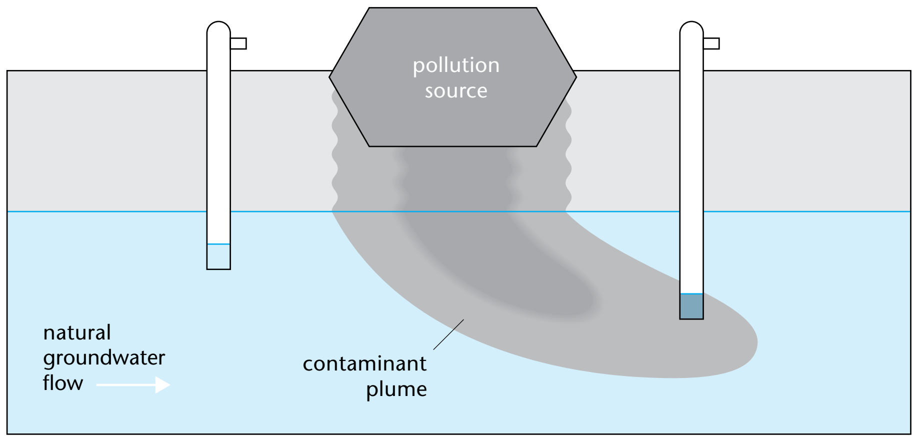
- Offensive Monitoring of Potential Pollution Sources. The objective is to provide early detection of incipient aquifer contamination by known sources of potential pollution, with monitoring immediately down hydraulic gradient, and analytical parameters chosen specifically, with respect to the pollution source. This approach is expensive and thus has to be highly selective, primarily targeting the more hazardous pollution sources located within groundwater supply capture zones in aquifers of high pollution vulnerability.
- Defensive Monitoring for Groundwater Supply Sources. The objective is to provide warning of pollution plumes threatening potable wellfields or individual waterwells and springs, through the installation of a monitoring network up hydraulic gradient, that is capable of detecting approaching polluted groundwater in time for further investigation and remedial action to be taken. A thorough understanding of the local groundwater flow system and contaminant transport pathways is required, (especially in relation to selection of the depths of monitoring borehole intakes), to avoid the possibility of by-pass of the defensive monitoring network.
- Evaluation Monitoring for Sites of Known Aquifer Contamination. A similar approach to that described under offensive monitoring should be adopted:
  - most importantly to confirm the effectiveness of natural contaminant attenuation processes, where these are considered to be the most economic or only feasible way to manage aquifer pollution
  - to confirm the effectiveness of remedial engineering measures taken to clean up or contain aquifer contamination, where these have been judged technically and economically feasible.

(C) Selection of Analytical Parameters

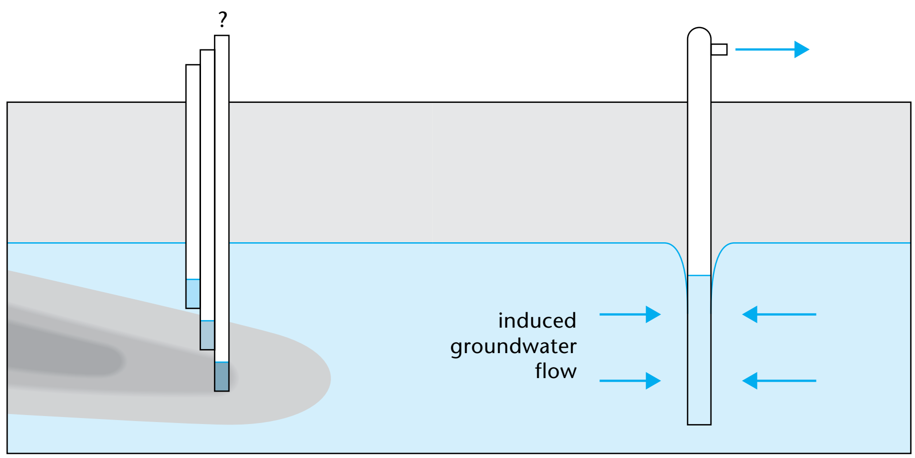
There is also pressing need to improve the selection of analytical parameters determined for groundwater samples. Routine monitoring of groundwater supply sources is widely limited to EC, pH, FC counts, and free Cl (if used for supply disinfection). Although these parameters give an indication of water purity, they provide very little information in relation to the presence or absence of the more frequent types of groundwater contamination. For

Figure 4.6 Schematic summary of groundwater quality monitoring strategies

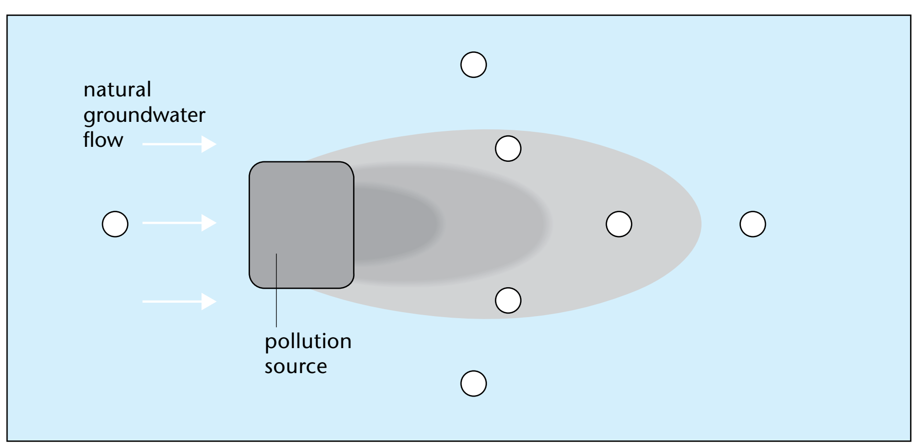
a) offensive detection monitoring for aquifer protection



b) defensive detection monitoring for water supply protection



c) evaluation monitoring of existing aquifer pollution incidents



example, if the waterwell was located in the vicinity of an industrial estate (including metal processing activity) it is essential to include monitoring for chlorinated industrial solvents and the heavy metals themselves, since the above monitoring schedule is unlikely to suggest their presence. The selection of monitoring parameters must be undertaken in the light of the groundwater pollution hazard assessment (Table A.2 in the Overview.).

The frequency of sampling in groundwater monitoring networks also has to be defined. Other than in aquifers of extreme or high pollution vulnerability, it will not normally be necessary to monitor aquifer groundwater quality more frequently than at three-month intervals.

4.5 Mounting Groundwater Quality Protection Programs

(A) Institutional Requirements and Responsibilities

In general terms, the water resource or environment regulator (or that agency, department, or office of national, regional, or local government charged with performing this function) is normally empowered to protect groundwater quality. In principle they are thus best placed to mount groundwater quality protection programs including:

- the establishment of land-surface zoning based on groundwater protection requirements
- the implementation of appropriate groundwater protection measures

although in practice they often lack the institutional resources and political commitment to act comprehensively or effectively.

It is critical that attention focuses down to the scale and level of detail necessary for the assessment and protection of specific water supply sources. To this end it is essential that water service companies become intimately involved. Moreover, given their responsibility to conform to codes of sound engineering practice, there would appear to be an obligation on water service companies themselves to take the lead in promoting or undertaking pollution hazard assessments for all their groundwater supply sources.

The procedures presented for groundwater pollution hazard assessment are the logical precursor to a program of protection measures. As such they provide a sound basis for forceful representations to be made to the local water resource and/or environment regulator for action on groundwater protection measures where needed. Even if no adequate pollution control legislation or agency exists, it will normally be possible to put pressure on the local government or municipal authority to take protective action under decree in the greater interest of the local population.

(B) Addressing Key Uncertainties and Challenges

Significant scientific uncertainties are likely to be present in many groundwater pollution hazard assessments, notably those related to:

- the subsurface attenuation capacity for certain synthetic organic contaminants
- the likelihood and scale of preferential vadose-zone flow in some geological strata
- the rates of water leakage and contaminant transport in some confining aquitards
- the groundwater flow regimes around waterwells in complex heterogenous aquifers,

which can lead to large error bands in the definition of protection requirements. The complication that this presents needs to be recognized (Reichard and others, 1990) and approached in an explicit and systematic way. In many instances it will be necessary in this context to obtain clear evidence of actual or incipient aquifer contamination through groundwater monitoring before it is possible to justify the cost of the necessary pollution control measures.

If the groundwater pollution hazard is confirmed it will then be necessary to appraise the risks that it presents and to define appropriate actions. In general, technical, and administrative terms, such actions could include:

- negotiation (and possible subsidy) of modifications to the design and operation of polluting activities, through the introduction of improved technology to reduce or eliminate subsurface contaminant load, with appropriate monitoring or remediation of existing groundwater contamination at the site
- transfer of the polluting activity to another (hydrogeologically less vulnerable) location, (in some cases with payment of compensation), with appropriate monitoring or remediation of existing groundwater contamination at the site
- relocation of groundwater supply sources to a new area of low pollution hazard, with the concomitant introduction of appropriate land-use development controls.

It should also be borne in mind that for some aquifers, or parts of aquifer systems, it will not be realistic to implement pollution protection, since their natural characteristics are such that poor quality groundwater is widely present. It will often be appropriate to designate such areas for the preferential location of industries or activities that have high probability of generating a heavy subsurface contaminant load. But in such cases it is important to evaluate carefully whether:

- the local groundwater may sometimes be used for small-scale domestic supply
- effluent infiltration could cause changes in groundwater flow direction that might threaten areas of better quality groundwater
- the construction of new waterwells or wellfields in adjacent areas could change the groundwater flow direction so as to be threatened by the neighboring groundwater contamination.

It also has to be recognized that shallow groundwater in urban areas is often likely to be significantly contaminated. Nevertheless, an integrated and coordinated approach including various of the following actions will often be beneficial in helping to protect

Box 4.2
Groundwater source pollution hazard evaluation and management around Managua, Nicaragua

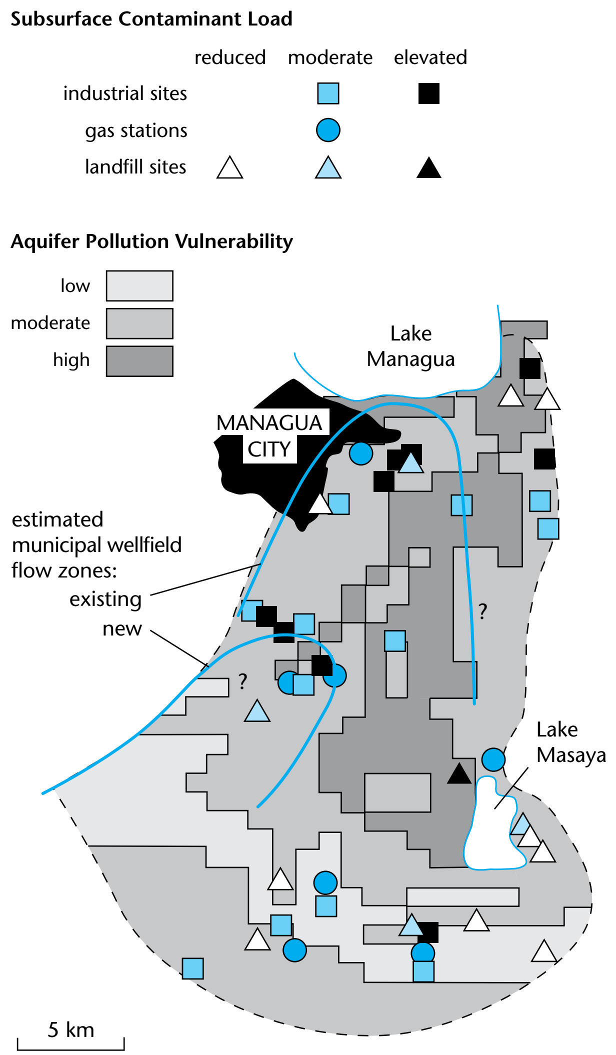
Systematic groundwater resource hazard evaluation, including aquifer vulnerability mapping and subsurface contaminant load survey with a clear policy to involve all stakeholders, has been carried out to protect major municipal wellfields.

- Groundwater is of the utmost importance for domestic, industrial, and agricultural water supply in the region and is extracted from deep municipal and private boreholes in a major volcanic aquifer system located south of Lake Managua. There is little soil development on the most recent lava flows, and this area is classified as highly vulnerable, despite the relatively deep water-table (more than 25 m bgl). The main existing wellfield abstracts some 195 Ml/d and is located in the urban fringe east of Managua City, but a new wellfield of 70-Ml/d at a more rural location some 10 km south of the city is under investigation and development.

- The capture zone of the existing wellfield is threatened by a range of industries including tanneries, metal workshops, and textile manufacturers in the Zona Franca industrial area, as well as fuel and chemical storage at the international airport and a number of developing periurban towns with in-situ sanitation (Scharp, 1994; Scharp and others, 1997, MARENA and KTH, 2000). There are also several small air strips in the area, which were historically used for storage, loading, and aerial spraying of agricultural land. In the past 30 years there was intensive cotton cultivation using many highly persistent pesticides, such as toxaphene and DDT.

- The predicted flow zone to the new wellfield is classified as having moderate vulnerability, but there are areas of high vulnerability due to the absence of soil cover, which has been removed through erosion. While there are a number of potential point sources of contamination from industry, gas stations, and waste disposal sites, only one industrial site with underground storage tanks has been classified as having high potential contaminant load. The capture area is more predominantly agricultural, and it is considered that the frequent use of mobile pesticides (such as the carbamate insecticides) poses the major pollution threat, and control over agricultural activity will be needed in the interests of municipal water supply.

Pollution assessment mapping for Managua groundwater system



potable groundwater supplies:

- prioritizing mains sewerage extension to areas of high aquifer pollution vulnerability, where aquifers are used at any scale for potable water supply
- improving the location and quality of wastewater discharge from mains sewerage systems, after consideration of the potential impacts on periurban and downstream municipal wellfields and other groundwater users
- restricting the density of new residential development served by conventional in-situ sanitation units
- constraining industrial effluent discharge to the ground through permits and charges, thereby stimulating effluent recycling, minimization, and treatment
- enforcing special handling requirements for persistent toxic chemicals and effluents at any industrial site located in areas of high aquifer pollution vulnerability
- directing the location of landfill solid-waste disposal facilities to areas of low aquifer pollution vulnerability.

There are also some further significant obstacles to the implementation of groundwater protection measures including:

- controlling diffuse agricultural practices, especially where this implies changes in crop or farm type as opposed to refining management of existing cropping practices and animal husbandry
- dealing technically and financially with the legacy of historic land and water contamination, especially in longer-standing industrialized areas
- lack of clarity over legal responsibility for serious (current and historic) groundwater pollution related to such questions as the timing of pollution incidents or episodes in relation to the introduction of legal codes, and whether the pollution occurred intentionally, knowingly, incidentally, or accidentally from the activity concerned
- resistance to land surface zoning for groundwater protection because of alleged reduction in land values (or property blight) resulting from implied lost opportunity or increased cost for industrial development or agricultural productivity.

(C) Creating a Consensus for Action

The control of groundwater pollution hazard requires taking technical action to achieve the reductions in subsurface contaminant load defined as priority from the preceding analysis. These actions have to be promoted within the social and economic framework of the area concerned, thus full stakeholder participation in the pollution hazard assessment and in the formulation of control measures will be essential for success.

Every effort should be made to make groundwater pollution hazard assessments transparent and available to civil society in general. A systematic socioeconomic assessment of the potential barriers to implementing groundwater protection measures (KTH and MARENA, 2000) will often provide key tactical information with which to frame and prioritize the action plan.

The procedures for groundwater pollution hazard assessment presented in this text constitute an effective vehicle for initiating the involvement of relevant stakeholders (especially water-user interests, but also potential groundwater polluters). This is (in part) because they facilitate communication through synthesis and simplification of hydrogeological conditions, while in essence still remaining scientifically based. In more general terms, land surface zoning through maps combining aquifer pollution vulnerability classes and groundwater supply capture areas (protection perimeters) can be readily used for the elaboration of acceptability matrices for various types of potentially polluting activity. Both are extremely valuable for:

- raising stakeholder awareness of groundwater pollution hazards
- offering a credible and defensible groundwater input to land-use planning procedures
- promoting public understanding of groundwater protection needs.

References

(references in blue used for text boxes)

Adams, B. and S. S. D. Foster. 1992. "Land-surface zoning for groundwater protection." Journal of Institution of Water and Environmental Management 6: 312–320.

Albinet, M. and J. Margat. 1970. "Cartographie de la vulnerabilite a la pollution des nappes d'eau souterraine." Bulletin BRGM 2nd Series 3(4): 13–22. Orleans, France.

Aller, L., T. Bennett, J. H. Lehr, R. J. Petty, and G. Hackett. 1987. DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. Environmental Protection Agency Report 600/2-87-035. Washington, D.C.

Andersen, L. J. and J. Gosk. 1987. "Applicability of vulnerability maps." TNO Committee for Hydrological Research: Proceedings and Information 38: 321–332. Delft, The Netherlands.

ASTM (American Society for Testing and Material). 1995. Standard guide for risk-based corrective action applied to petroleum release site. ASTM Designation E1739-95. Washington, D.C.

Barbash, J. E. and E. A. Resek. 1996. Pesticides in ground water: distribution, trends, and governing factors. Chelsea, Michigan: Ann Arbor Press.

Bates, L. E., C. Barber, J. Ross, and J. Verhoeven. 1993. "Vulnerability of groundwater to pollution: evaluation of the DRASTIC system in the Peel river catchment, northern New South Wales, Australia." Proceedings of Australian National University Conference: Aquifers at Risk. Canberra, Australia.

Blarasín, M., C. Eric, C. Frigerio, and S. Bettera. 1993. "Determinación del riesgo de contaminación del acuífero libre por sistemas de saneamiento in situ: ciudad de Río Cuarto." Dpto. Río Cuarto, Córdoba, Argentina. Publicación Especial de la Asociación Argentina de Geología Aplicada a la Ingeniería 1: 114–131.

Blarasín, M., A. Cabrera, M. Villegas, C. Frigerio, and S. Bettera. 1999. Groundwater contamination from septic tanks system in two neighborhoods in Río Cuarto City, Córdoba, Argentina. International Association of Hydrogeologists–International Contributions to Hydrogeology 21: 31–38.

Bernardes, Jr. C., R. Hirata, J. Mendes, and R. Cleary. 1991. "Remedial action for an industrial open dump-proposed activities and prospectives." Water Science and Technology 24(11): 271–281.

BNA (U.S. Bureau of National Affairs). 1975. Water Pollution Control. BNA Policy and Practice Series. Washington D.C.

Burmaster, D. and J. Learh. 1991. "It's time to make risk assessment a science." Ground Water Monitoring and Remediation 11(3):5–15.

Carter, A. D., R. C. Palmer, and R. A. Monkhouse. 1987. "Mapping the vulnerability of groundwater to pollution from agricultural practice particularly with respect to nitrate." TNO Committee for Hydrological Research: Proceedings and Information 38: 382–390. Delft, The Netherlands.

Cheremisinoff, P. 1992. A guide to underground storage tanks evaluation, site assessment and remediation. New Jersey: Prentice-Hall.

Chilton P. J., A. A. Vlugman, and S. S. D. Foster .1990. "A Groundwater pollution risk assessment for public water supply sources in Barbados." American Water Resources Association International Conference on Tropical Hydrology and Caribbean Water Resources 279–289. San Juan de Puerto Rico.

Daly, D., A. Dassargues, D. Drew, S. Dunne, N. Goldschneider, N. Neale, I. C. Popescu, and F. Zwahlen. 2001. "Main concepts of the European approach for karst groundwater resource assessment and mapping." IAH Hydrogeology Journal 10: 340–345.

Daly, D. and W. P. Warren. 1998. "Mapping groundwater vulnerability: the Irish perspective." Geological Society Special Publication 130: 179–190.

DMAE (Departamento Municipal de Água e Esgotos). 1981. "Equivalentes populacionais de resíduos líquidos industriais da região metropolitana de Porto Alegre." Informe 27. Porto Alegre, Brazil.

Doerfliger, N., and F. Zwahlen. 1998. Practical guide to groundwater vulnerability mapping in karstic regions. Berne, Switzerland: A Swiss Agency for Environment, Forest & Landscape Publication.

EA (Environment Agency). 1998. Policy and practice for the protection of groundwater. London: HMSO.

Fetter, C. 1988. Applied hydrogeology. New York: Macmillan Publishing Company.

Foster, S. S. D. 1985. Groundwater pollution protection in developing countries. IAH Intl. Contrl Hydrogeology. International Association of Hydrogeologists–International Contributions to Hydrogeology 6: 167–200.

—— 1987. "Fundamental concepts in aquifer vulnerability pollution risk and protection strategy." Proceedings of International Conference: Vulnerability of Soil and Groundwater to Pollutants. Noordwijk, The Netherlands.

Foster, S. S. D., B. Adams, M. Morales, and S. Tenjo. 1993. "Groundwater protection strategies: a guide towards implementation." UK ODA, CPR, WHO/PAHO-HPE Technical Manual. Lima, Peru. 88pp.

Foster, S. S. D., P. J. Chilton, and M. E. Stuart. 1991. "Mechanisms of groundwater pollution by pesticides." Journal of Institution of Water and Environmental Management 5: 186–193.

Foster, S. S. D., A. C. Cripps, and A. K. Smith Carington. 1982. Nitrate leaching to groundwater. Philosophical Transactions of Royal Society of London 296: 477–489.

Foster, S. S. D. and D. C. Gomes. 1989. "Groundwater quality monitoring: an appraisal of practices and costs." WHO-PAHO/HPE-CEPIS Technical Manual. Lima, Peru.

Foster, S. S. D. and R. Hirata. 1988. "Groundwater pollution risk assessment: a methodology using available data." WHO-PAHO/HPE-CEPIS Technical Manual. Lima, Peru.

Foster, S. S. D., A. R. Lawrence, and B. L. Morris. 1998. "Groundwater in urban development: assessing management needs and formulating policy strategies." World Bank Technical Paper 390. Washington, D.C.

Foster, S. S. D. and A. C. Skinner. 1995. "Groundwater protection: the science and practice of land surface zoning." International Association of Hydrological Sciences 225: 471–482.

Gillham, R. and J. Cherry. 1989. Refuse disposal sites and their long-term behavior. Dusseldorf, Germany: ENVITEC.

Hackman, E. E. 1978. "Toxic organic chemicals: destruction and waste treatment." Pollution Technology Review 40.

Haertle, A. 1983. "Method of working and employment of EDP during the preparation of groundwater vulnerability maps." International Association of Hydrological Sciences 142: 1073–1085.

Hirata, R. 1993. "Os recursos hídricos subterrâneos e as novas exigências ambientais." Revista do Instituto Geológico de São Paolo 14(1): 39–62.

Hirata, R., C. Bastos, and G. Rocha. 1997. "Mapa de vulnerabilidade das águas subterrâneas no Estado de São Paulo." Instituto Geológico, Companhia de Saneamento Ambiental, Departamento de Águas e Energia Elétrica. São Paulo, Brasil. 2 vol.

Hirata, R., C. Bastos, G. Rocha, D. Gomes, and M. Iritani. 1991. "Groundwater pollution risk and vulnerability map of the São Paulo State - Brasil." Water Science and Technology 24(11): 159–169.

Hirata, R. and A. Rebouças. 1999. "La protección de los recursos hídricos subterráneos: una visión integrada, basada en perímetros de protección de pozos y vulnerabilidad de acuíferos." Boletín Geológico Minero de España 110 (4): 423–436.

Hirata, R., G. S. Rodrigues, L. C. Paraíba, and C. C. Buschinelli. 1995. Groundwater contamination risk from agricultural activity in São Paulo State (Brasil). BGS (British Geological Survey) Technical Report WD/95/26: 93–101. Nottingham, U.K.

Holden, L.R., J. A. Graham, R. W. Whitmore, W. J. Alexander, R. W. Pratt, S. K. Liddle, and L. L. Piper. 1992. "Results of the national alachlor waterwell survey." Environmental Science and Technology 26: 935–943.

Johansson, P.O. and R. Hirata. 2001. Rating of groundwater contamination sources. In: Zaporozec, A., ed., Groundwater contamination inventory: A methodological guideline. Paris, France: UNESCO.

Kalinski, R. J., W. E. Kelly, I. Bogardi, R. L. Ehrman, and P. D. Yamamoto. 1994. "Correlation between DRASTIC vulnerabilities and incidents of VOC contamination of municipal wells in Nebraska." Ground Water 32(1): 31–34.

Kolpin, D. W., J. E Barbash., and R. J. Gilliom. 2000. "Pesticides in ground water of the United States, 1992–1996." Ground Water 38(6): 858–865.

Kostecki, P. T. and E. Calabrese. 1989. Petroleum contaminated soil: remediation techniques, environmental fate, and risk assessment. Vol I. Mich.: Lewis Publishers.

KTH and MARENA. 2000. "Identificación de barreras a la protección sostenible del agua subterranea. Ministerio del Ambiente y Recursos Naturales Informe. Managua, Nicaragua.

Lewis, W. J., S. S. D. Foster, and B. Drasar. 1982. The risk of groundwater pollution by on-site sanitation in developing countries. WHO-PAHO/HPE-CEPIS Technical manual. Lima, Peru.

Lloyd, B. and R. Helmer. 1991. Surveillance of drinking water quality in rural areas. WHO-UNEP Publication. Longman Scientific and Technical. London, U.K.

Loague, K. 1994. "Regional scale groundwater vulnerability estimates: impact of reducing data uncertainties for assessments in Hawaii." Ground Water 32: 605–616.

Luin, A. B. Van and W. Van Starkenburg. 1985. "Behaviour of contaminants in groundwater." Water Science and Technology 17: 843–853.

Mackey, D. and J. Cherry. 1996. "Groundwater contamination: pump and treat remediation." Environmental Science and Technology 23: 630–636.

MARENA and KTH. 2000. "Estimación del peligro potencial de contaminación en el acuifero de Managua." Ministerio del Ambiente y Recursos Naturales Informe. Managua, Nicaragua.

Martin, P. J., D. C. Gomes, M. Iritani, and N. Guiguer. 1998. "An Integrated Groundwater Management Using Modeling and GIS. Proceedings of the Groundwater in a Watershed Context Symposium," Section 3: 137–145. Canada Centre for Inland Waters, Burlington, Ontario.

Mazurek, J. 1979. "Summary of modified Le Grand method." National Center for Ground Water Research Report. Norman, Oklahoma.

Miller, D. and M. Scalf. 1974. "New priorities for groundwater quality protection." Ground Water 12: 335–347.

Monkhouse, R. A. 1983. "Vulnerability of aquifers and groundwater quality in the United Kingdom." Institute of Geological Sciences Report. Nottingham, U.K.

Morris, B. L. and S. S. D. Foster. 2000. "Cryptosporidium contamination hazard assessment and risk management for British groundwater sources." Water Science and Technology 41 (7): 67–77.

Nemerow, N. L. 1963. Theories and practices of industrial waste treatment. Reading, Mass.: Addison-Wesley.

—— 1971. Liquid waste of industry: theories and practices of industrial waste treatment. Reading, Mass.: Addison-Wesley.

Nicholson, R., J. Cherry, and E. Readon. 1983. "Migration of contaminants in groundwater at a landfill: A case study, 6. Hydrogeochemistry." Journal of Hydrology 63(1/2): 131–176.

NRA (National Rivers Authority). 1995. Guide to groundwater protection zones in England and Wales. London: HMSO.

NRC (National Research Council). 1993. Groundwater vulnerability assessment: contamination potential under conditions of uncertainty. Washington, D.C.: National Academy Press.

Paez G. 1999. Evaluación de la vulnerabilidad a la contaminación de las aguas subterráneas en el Valle del Cauca. Informe Ejecutivo. CorpoRegional del Valle del Cauca. Cauca, Colombia.

Pankow, J., R. Johnson, J. Houck, S. Brillante, and W. Bryan. 1984. "Migration of chlorophenolic compounds at the chemical waste disposal site at Alkali Lake, Oregon. 1, Site description and groundwater flow." Ground Water 22(5): 593–601.

Paris, M., O Tujchneider., M. D'Elia, and M. Perez. 1999. "Hidrogeología Urbana: Protección de Pozos de Abastecimiento en la Gestión de los Recursos Hídricos Subterráneos." Revista Serie Correlación Geológica 13: 153–160.

Reichard, E., C. Cranor, R. Raucher, and G. Zapponi. 1990. "Groundwater contaminant risk assessment: A guide to understanding and managing uncertainties." International Association of Hydrological Sciences. Wallingford, U.K.

Rosen, L. 1994. "A study of the DRASTIC methodology with emphasis on Swedish conditions." Ground Water 32(2): 278–285.

Sax, N. 1984. Dangerous properties of industrial materials, sixth edition. New York: Van Nostrand Reinhold.

Scharp, C. 1994. "Groundwater Protection Plan for the Managua Aquifer development of Planning Tool." International Association of Hydrogeologists 222: 443–451.

Scharp, C., T. Alveteg, P. O. Johansson, and M. Caldera. 1997. "Assigning a groundwater protection value: methodology development." Proceedings of International Association of Hydrogeologists Congress: Problems, Processes and Management. Nottingham I: 659–664.

Sokol, G., C. Leiburgit, K. P. Schulz, and W. Weinzierl. 1993. "Mapping procedures for assessing groundwater vulnerability to nitrates and pesticides in Application of Geographic Information System in Hydrology and Water Resources Management." International Association of Hydrological Sciences 211: 80–92.

Stuart, M. and C. Milne. 1997. "Groundwater quality implications of wastewater irrigation in León, México." Proceedings of International Association of Hydrogeologists Congress: Problems, Processes and Management. Nottingham I: 193–198.

Thomann, R., J. Lobos, H. Sallas, and J. Dos Santos. 1987. "Manual de evaluación y manejo de sustancias tóxicas en aguas superficiales (3). Evaluación preliminar del problema." WHO/PAHO-CEPIS Technical Report. Lima, Peru.

UNEP (United Nations Environmental Programme). 1988.

"Environmental impact assessment: basic proceedings for developing countries." Internal Guidebook. Geneva, Switzerland.

EPA (Environmental Protection Agency). 1977. Procedures manual for groundwater monitoring of solid waste disposal facilities. Report EPA-530-SW-61. Washington, D.C.

——. 1980a. Treatability manual (2) industrial description. Report EPA-600-8-80-042B. Washington, D.C.

——. 1980b. Procedures manual for groundwater monitoring at solid waste disposal facilities: Report SW-611. Washington, D.C.

——. 1991. "Guide for conduction contaminant source inventories for public drinking water supplies: technical assistance document." Environmental Protection Agency, Office of Water, Washington, D.C.

——. 1994. Handbook on groundwater and wellhead protection. Environmental Protection Agency, Washington, D.C.

Vrba, J. and E. Romijn. (eds.) 1986. "Impact of agricultural activities on groundwater." International Association of Hydrogeologists–International Contribution to Hydrogeology 5.

Vrba, J. and A. Zaporozec. 1994. "Guidebook on mapping groundwater vulnerability." International Association of Hydrogeologists–International Contributions to Hydrogeology 16.

Weitzenfeld, H. 1990. "Manual básico de evaluación del impacto en el ambiente y la salud de proyectos de desarrollo." ECO-OPS/OMS. Metepec, México. 198 pp.

WHO (World Health Organization). 1982. "Rapid assessment of sources of air water and land pollution." World Health Organization Offset Publication 62. 113pp.

Zaporozec, A. and J. Miller. 2000. Groundwater pollution. Paris, France: UNESCO.

Zaporozec, A. 2001. Contaminant source inventory. In: Zaporozec, A. (ed.) Groundwater contamination inventory. A methodological guideline. Paris, France: UNESCO.

GW·MATE
Groundwater Management Advisory Team

bnwpp
Bank-Netherlands Water Partnership Program

DFID Department For International Development

WHO-PAHO Pan American Center for Sanitary Engineering & Environmental Sciences (CEPIS)

UNESCO
UNESCO-IHP Regional Office for Latin America and the Caribbean

Groundwater is a vital natural resource for the economic and secure provision of a potable water supply. All too often in the past aquifers have been abandoned to chance, and those who depend upon them for the provision of potable water supplies have done little to protect their sources. Proactive campaigns and practical actions to protect the quality of groundwater are widely and urgently required. This Guide has been produced to emphasize that groundwater pollution hazard assessment and protection measures must become an essential part of environmental best practice. Groundwater Quality Protection comprises two parts:

- an Executive Overview for water utility senior personnel, municipal authorities, and environment agencies that answers their anticipated questions on groundwater pollution hazard assessment and the development of groundwater protection strategy
- a Technical Guide for professional groundwater specialists, environmental engineers, and scientists involved in undertaking the detailed work of mapping, aquifer pollution vulnerability, delineation of groundwater supply protection areas, inventory of subsurface contaminant load, and the assessment and control of groundwater pollution hazards.

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