

Section III

Situation analysis

14

Assessment of groundwater pollution potential

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Using the knowledge of the regional groundwater conditions and the nature of the human activities and their possible impacts on groundwater quality provided by Sections I and II, this chapter describes the assessment of groundwater pollution potential, and illustrates the approach with two case studies. The intention of the chapter is to indicate the general scope and scale of what is required to assess groundwater pollution potential, rather than to provide detailed technical guidance on how it should be done. This more detailed technical material, aimed more at the practising professional actually carrying out such an assessment, can be found in, for example, Foster *et al.* (2002) and Zaporozec (2002). Chapter 15 builds on this assessment to provide guidance on establishing groundwater management priorities to reduce the impact of pollution, either by increasing the protection measures at drinking-water sources (Section IV) or by controlling pollution sources and the activities causing pollution (Section V).

Assessment of groundwater pollution potential in a given drinking-water catchment may be conducted under a wide variety of conditions and at varying spatial scales and levels of sophistication (Foster and Hirata, 1988). As a result, the assessment can produce a wide range of outcomes. The conditions may range from simple settings with almost self-evident identification of one or two key hazards (e.g. high density of poorly sealed latrines on a shallow aquifer) to highly complex urban and industrial scenarios with

diverse human activities, in which the key sources of pollution are difficult to identify. This complexity may perhaps be coupled with small-scale variations in geology and hydrogeological conditions, rendering vulnerability assessments equally demanding. This broad variation means that assessments of pollution potential can require an equally broad range of sophistication, ranging from reconnaissance surveys of the major potential sources of groundwater pollution to detailed surveys of chemical or microbial pollutant loads and even to simple modelling of, for example, the leaching potential of pesticides used in the catchment. This implies that experienced professionals from the hydrogeology and environmental engineering disciplines will normally be needed, both to help decide on the level of sophistication required, and to undertake the assessment itself.

NOTE ► *This chapter indicates the general scope and scale of what is required to assess groundwater pollution potential, rather than providing detailed technical guidance on how it should be done. In the context of developing a Water Safety Plan this chapter supports risk assessment for groundwater fed drinking-water supplies.*

14.1 THE OVERALL ASSESSMENT PROCESS

Prior to undertaking the assessment of groundwater pollution potential, the first exercise is to decide upon the area to be protected around the drinking-water source. This may include the entire extent of the aquifer system in which the source occurs at one extreme, or may involve delineating the specific catchment or zone of influence of the supply source or sources in question. This will normally be the hydrogeologically-defined capture zone from which the recharge is derived, as in the Barbados case study (Section 14.5), or may just be a simple radius around the source. Guidance is given in Chapter 17 on the establishment of such zones. Once the area of investigation has been defined, then the process described below can be undertaken. However, it is important to note that groundwater catchments do not always follow surface water catchments and may cross both local and national administrative political boundaries. Thus selection of the correct and appropriate area is critical. Near national borders, it may even involve international discussions and agreements for successful implementation of groundwater protection and the associated control measures or other management responses.

In view of the complexity of factors affecting pollutant migration and the uniqueness of each field situation, it would be logical to treat each activity or source on individual merit and undertake independent field investigations to assess pollution potential (Foster and Hirata, 1988). However, because of the high cost of such investigations, simpler but consistent procedures for assessing pollution potential at modest cost are needed. The reader should not, therefore, be unduly discouraged by the complexity of hydrogeological conditions and pollutant behaviour. Using the understanding of the former gained from Chapters 2 and 8, and of the latter from Chapters 3, 4, and 9 to 13,

useful assessments of groundwater pollution potential can be achieved on the basis of existing information combined with some field reconnaissance.

As shown in Figure 14.1, the potential for groundwater pollution to occur is determined by the interaction between the microbial or chemical pollutant loading which is being, or might be, applied to the subsurface environment as a result of one or more of the types of human activity described in Chapters 9-13, and the aquifer vulnerability, which depends on the intrinsic physical characteristics of the soil and strata separating the aquifer from the land surface, as described in Chapter 8.

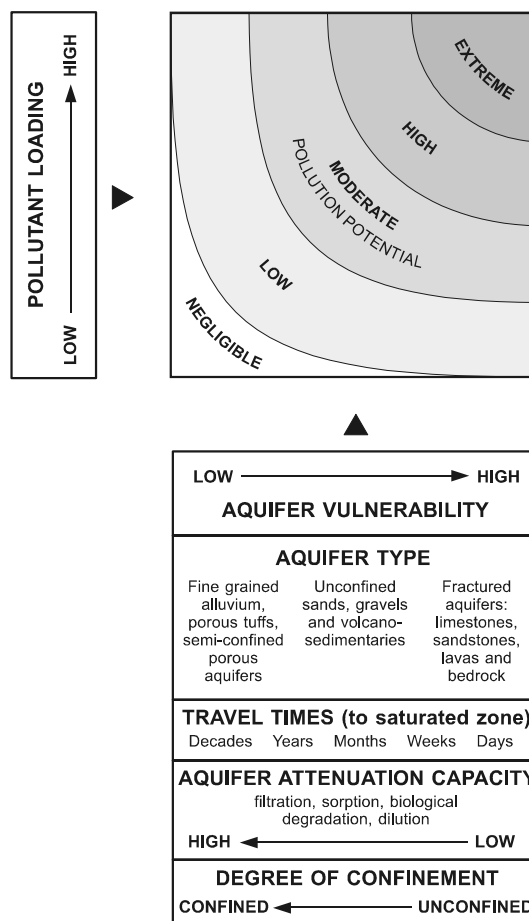


Figure 14.1. Groundwater pollution potential (adapted from Foster and Hirata, 1988)

The factors that define aquifer vulnerability (Chapter 8) are summarized here for convenience along the horizontal axis of Figure 14.1, and it is the identification and characterization of the factors that determine pollutant loading on the vertical axis that is the subject of this chapter.

The matrix in Figure 14.1 does not assign quantitative scores, but rather depicts a relative classification of pollution potential, and the components of both pollutant loading and aquifer vulnerability can have broad ranges from low to high. Thus a combination of high pollutant loading and high aquifer vulnerability provide the most extreme pollution potential in the top right corner of the figure. Adopting this approach, it is possible to envisage situations in which an aquifer is highly vulnerable, but there is little or no danger of pollution because there is no pollution load, or vice versa. Both are consistent in practice. The former might occur on an uninhabited coral limestone island, and the latter where an urban area with many small pollution sources is separated from an underlying deep aquifer by a thick sequence of impermeable clays or silts.

Whether the pollution potential derived in this way will be translated into a serious quality impact producing problems for drinking-water supplies using groundwater will depend on several factors. These include the mobility and persistence of the pollutants within the groundwater flow regime and the scope for further dilution in the saturated zone. The economic and financial scale of the impact will depend on the value of the groundwater resources affected, including the investment and operating costs in abstracting the water and delivering it to consumers, and the cost of finding alternative supplies, as well as the broader societal and environmental value of the groundwater where, for example, there are many small-scale community or private wells and boreholes.

If the relationship in Figure 14.1 could be fully quantified in probability terms, it would become a more formal indication of the likelihood that groundwater in an aquifer would become polluted at concentrations above respective guideline values. While this may be possible for some diffuse pollution sources such as agriculture and unsewered sanitation, experience suggests it is much more difficult to quantify microbial and chemical pollutant loads to groundwater for most point sources. Further, given the uncertainties about pollutant behaviour outlined below and in Sections I and II, a qualitative or semi-quantitative assessment of the potential for pollution of groundwater to occur is, for many settings, the best that situation analysis can achieve. This is, however, likely to be more than adequate as a basis for initiating consideration of actions for protecting groundwater, and for focussing more detailed investigation or monitoring on the activities or sources judged to be the most significant.

14.2 COMPONENTS OF ASSESSMENT OF POLLUTANT LOADING

The series of questions that need to be answered in an assessment of pollutant loading are shown in Figure 14.2. The six questions and the associated components of the assessment are presented one above the other, and linked sideways by arrows to the box representing pollutant loading to denote that they are not necessarily part of a sequential decision process. The information needed to answer these questions must come from a survey or inventory of likely pollutant sources, including identification, location and characterization of all sources, including where possible their historical evolution (see checklists at the end of chapters of Section II). Further discussion of data collection procedures and design and implementation of pollution inventories is provided by Foster *et al.* (2002) and Zaporozec (2002).

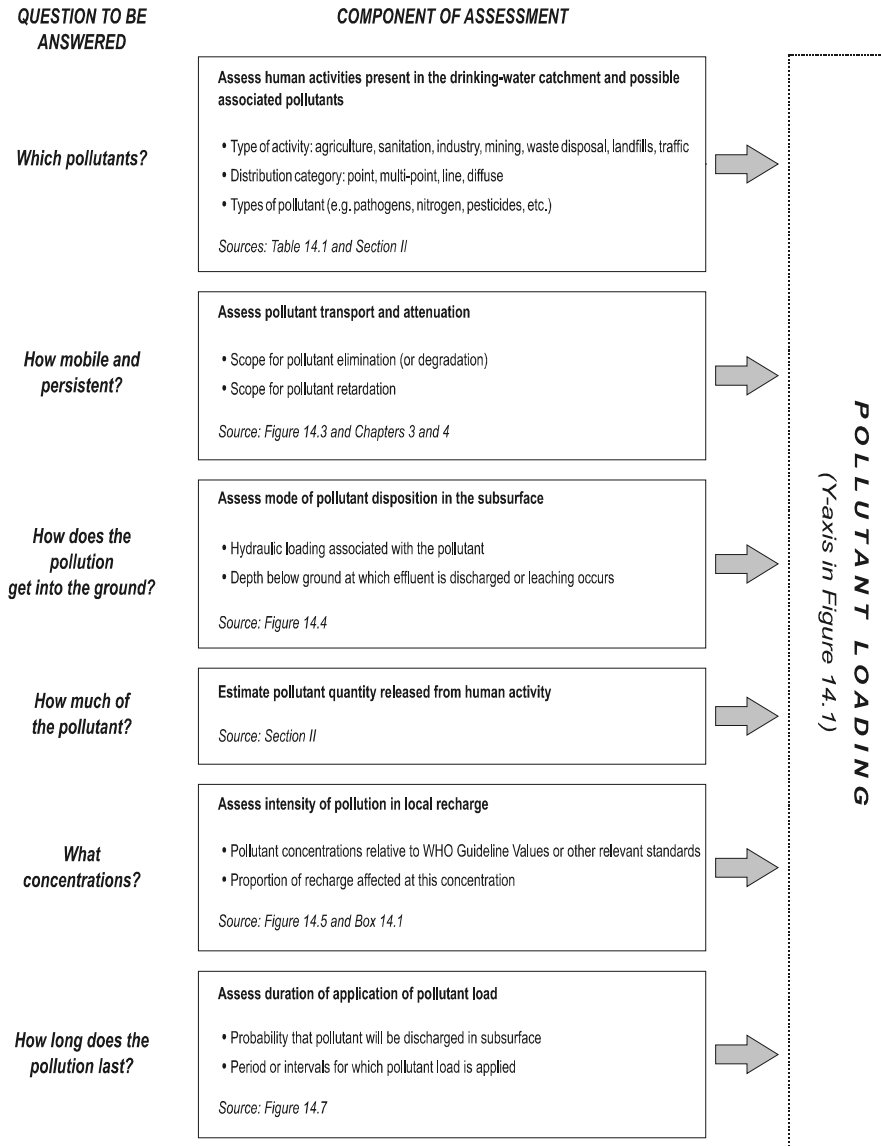


Figure 14.2 Components of assessment of pollutant loading

The information needed to answer the first question in Figure 14.2 is summarized in Table 14.1, in which the human activities in Chapters 9-13 are listed with many of the main types of pollutants and their category of distribution as point, line or diffuse sources. Table 14.1 also indicates which of the activities are accompanied by significant hydraulic loading by additional volumes of water, and for which of them the protective soil layer is by-passed in the method of usage or disposal of the potential pollutants.

Table 14.1. Summary of activities potentially generating subsurface pollutant loading (modified from Foster *et al.*, 2002)

Type of human activity	Character of pollutant loading			
	Distribution category	Main types of pollutant	Relative hydraulic loading	By-pass of soil zone
Agriculture (Chapter 9)				
<i>Cultivation with:</i>				
Agrochemicals	D	<i>NP</i>		
Irrigation	D	<i>NPS</i>	+	
Sewage sludge and wastewater	D	<i>FNOS</i>	+	
<i>Animal feedlot operation:</i>				
Leakage from unlined effluent lagoons	P	<i>FN</i>	++	+
Land discharge of effluent	P-D	<i>FNS</i>	+	
Sanitation (Chapter 10)				
Leakage from on-site sanitation	P-D	<i>FN</i>	+	+
Land discharge of sewage	P-D	<i>FNOS</i>	+	
Leakage from sewage oxidation lagoons	P	<i>FNO</i>	++	+
Sewer leakage	P-L	<i>FNO</i>	+	+
Industry (Chapter 11)				
Leakage from effluent lagoons (process water)	P	<i>OMS</i>	++	+
Tank and pipeline leakage	P	<i>OM</i>	+	+
Accidental spillages	P	<i>OM</i>	++	
Land discharge of effluent	P-D	<i>OMS</i>	+	
Well disposal of effluent	P	<i>OMS</i>	++	+
Mining (Chapter 11)				
Mine drainage discharge	P-L	<i>MSA</i>	++	+
Leakage from sludge lagoons (process water)	P	<i>MSA</i>	++	+
Leaching from solid mine tailings	P	<i>MSA</i>		+
Oilfield brine disposal	P	<i>S</i>	+	++
Waste disposal and landfill (Chapter 12)				
Leaching from waste disposal/landfill sites	P	<i>NOMS</i>		++
Traffic (Chapter 13)				
Highway drainage soakaways	P-L	<i>OMS</i>	++	++
Tank leakage	P	<i>O</i>	+	+
Application of chemicals	P-L	<i>PS</i>		
Groundwater resource management (Chapter 8)				
Saline intrusion	D-L	<i>S</i>		
Recovering water levels	D	<i>OSA</i>		
Drawdown of pollutants due to abstraction	D	<i>OMS</i>		
Wellhead contamination	P	<i>FN</i>		++

Distribution category: P – point; D – diffuse; L – linear. Main types of pollutant: *F* – faecal pathogens; *N* – nutrients; *O* – organic compounds including chlorinated solvents or aromatic hydrocarbons (BTEX); *P* – pesticides; *M* – metals; *S* – salinity; *A* – acidification

Relative hydraulic loading: + to ++ (increasing importance; relative volume or impact of water entering with pollution load). By-pass of soil zone: + to ++ (with completeness of by-pass of soil and depth of penetration into unsaturated and saturated zones)

A simple approach to illustrating four of the components of Figure 14.2 is shown in Figures 14.3 to 14.5 and 14.7. These are based on diagrams originally developed by Foster and Hirata (1988), but modified to refer to the groups of human activities described in Chapters 9-13 and summarized in Table 14.1.

The four diagrams presented here are intended to be used conceptually, i.e. to provide a general and largely relative indication of which features of the selected activities contribute most to the potential for pollution of groundwater to occur. Qualitative interpretation of the four diagrams will help to indicate where efforts to improve the information base should be concentrated. Experience of assessing pollutant loading potential, including in the two case study examples, suggests that, in many situations, the complexity of human activities, industrial processes and waste disposal practices means that careful and detailed investigations using the checklists from Chapters 9-13 are required.

Pollutant mobility and persistence

Figure 14.3 helps to answer the question about mobility and persistence by locating the main classes of pollutants according to their potential for degradation and elimination or pathogen inactivation and die-off respectively, and/or retardation by the processes described in Chapters 3 and 4. The former include chemical reactions such as precipitation and complexation as well biodegradation, and the latter comprise adsorption, filtration and cation exchange. Thus mobile and persistent pollutants such as chloride and nitrate are relatively little affected by these attenuation processes in aerobic conditions in the aquifer and the overlying strata. For these pollutants, dilution will usually be the main attenuation process that operates. More readily degraded and retarded pollutants such as pesticides, bacteria and viruses can be significantly restricted from reaching aquifers if the overlying strata have adequate attenuation capacity in terms of clay and organic carbon content and microbial activity.

While Figure 14.3 is helpful conceptually, it is emphasized that this general guide has limitations. Firstly, pollutants within the simple groupings given in Figure 14.3 may behave differently, and for hydrocarbons and pesticides the tables in Chapter 4 and the references from which they were derived can provide more specific information. Secondly, while the aerobic, alkaline conditions specified in the title are the most common and widespread in groundwaters, changes in pH and Eh conditions can have important influences on mobility and persistence (Lyngkilde and Christensen, 1992; Christensen *et al.*, 1996). Eh, the redox potential, is a measure (usually in millivolts) of the intensity of oxidizing or reducing conditions within a groundwater system. Positive potentials indicate that the system is relatively oxidizing, and negative potentials represent reducing conditions (Hem, 1985). The influence on pollutant groups of reductions in pH or Eh, representing more acidic and reducing conditions respectively, is shown in Figure 14.3. Thus most metals become significantly more mobile in acidic and/or reducing conditions, and ammonium and nitrate are mutually sensitive to the oxidation status of the groundwater. Some pollutants, in particular arsenic and chromium, have several forms of natural occurrence. These can have different chemical valencies or oxidation status, and their possible behaviour in response to changes in acidity or oxidation status is too complex to be represented simply on Figure 14.3.

A final note of caution is that the figure can be considered broadly applicable to aquifers in which groundwater movement is intergranular or in a network of small fractures (Chapter 2). In the very rapid groundwater flow conditions of karstic aquifers, however, water and microbial and chemical pollutants may be moving so fast that the processes of elimination and retardation do not have time to operate.

Even allowing for these cautionary notes, the likelihood of reaching groundwater can be assessed in qualitative terms for potential pollutants identified or anticipated from the situation assessment and from Table 14.1. This likelihood increases from bottom left to top right of Figure 14.3.

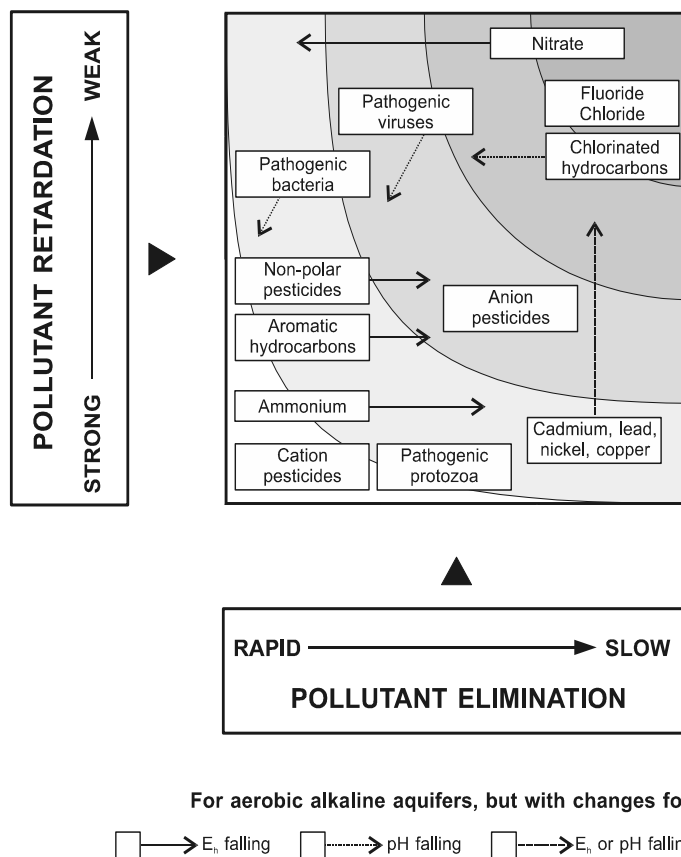


Figure 14.3. Characterization of mobility and persistence of pollutants in aerobic, alkaline conditions (adapted from Foster and Hirata, 1988)

Mode of disposition

The next characteristic of pollutant loading potential (Figure 14.2) is the mode of disposition, i.e. how the pollutant enters the subsurface. This is a combination of the hydraulic loading or surcharge associated with or imposed by the pollution source, and

the depth below the ground surface at which either effluent is discharged or leaching from solid residues occurs, and is illustrated in Figure 14.4.

Thus conventional, rainfed agriculture takes place at the ground surface with a hydraulic loading only from infiltrating rainfall. Irrigated agriculture may produce significantly higher hydraulic loading, depending on the number of crops per year and type of crops, and the irrigation methods used. Many other potential sources of pollution originate below the soil – including leaking sewers, unsewered sanitation, industrial effluents and soakaway drainage from highways. Depending on the precise mode of disposition, the pathway to groundwater may be greatly shortened for several of these, as depicted in Figure 14.4. Unlined landfills can generate highly concentrated leachates which may enter the subsurface at considerable depth if the waste has been disposed of in excavations formerly used for quarries or pits. Disposal of industrial effluents into old wells or specially constructed disposal wells transports pollutants directly to the water table, often with significant local hydraulic loading (Figure 14.4). An accidental spill at the land surface may have apparently limited potential to cause groundwater pollution. However, highways, railways and airfields often drain to the subsurface by soakaways, greatly facilitating more rapid transport of pollutants to groundwater (Figure 14.4). The potential to cause pollutant loading, and likely scale of impact, increases from bottom left (small loading at the ground surface) to top right (high hydraulic loading close to or at the water table).

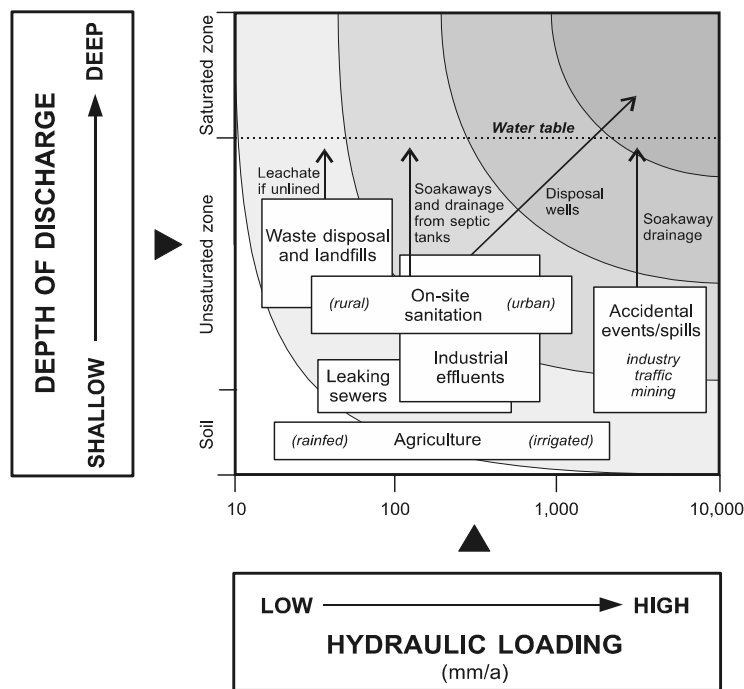


Figure 14.4. Characterization of mode of pollutant disposition (adapted from Foster and Hirata, 1988)

Pollutant quantity

Within a general assessment of potentially polluting activities, it is clearly desirable to obtain as much information as possible about each of the components shown in Figure 14.2. Thus in answer to the question about how much of the pollutant is initially released by or leached from the human activity in question, it would ideally be possible to estimate the actual quantities of pollutants at the time and place of release into the environment. For pathogens or faecal indicators these would usually be expressed in counts of organisms per 100 millilitre, and for chemicals in units such as litres or kilograms of, for example, D/dense/light non-aqueous phase liquid (D/LNAPL) spilled in an accident or leaked from a tank or pipeline, kilograms of nitrogen fertilizer applied per ha, or cubic metres of landfill leachate and the concentrations of pollutants in the leachate. Because of the infinite variety of scope and scale of human activities that potentially generate pollutants (Table 14.1), a simple tabulation of quantities, estimation methods or published sources that could be used to answer the question 'how much pollutant?' is not feasible. While some indications of pollutant quantities for some activities such as nitrogen fertilizer applications and leaching losses (Conway and Pretty, 1991), unsewered sanitation (ARGOSS, 2001) and landfill leachates (Stuart and Klinck, 1998) can be obtained from literature sources, for the most part estimates of pollutant quantities must be attempted for the specific situation encountered.

For a few types of individual point sources, estimating the quantity of pollutant released may be a simple matter of site observation, for example, the volume of liquid leaked from a ruptured road or rail tanker, or a catastrophic failure of a fuel tank, tailings dam or similar structure of known volume. For the majority of even apparently 'simple' point sources, pipelines, broken sewers, landfills, lagoons, dams and tanks, leakage is likely to have been slow, intermittent or continuous over considerable time periods, and from storage or conveyance systems with largely unknown but probably variable discharges and pollutant concentrations. Further, the complexity and considerable diversity of many of the major potential pollutant sources and the fact that, especially in urban areas, sources may be spatially distributed over a large area, such as to cause a complex mosaic of many small pollution sources, means that the load from and consequent impact of any individual one is very difficult to isolate. In the case of the city of Leon in Mexico, for example, which is a centre of leather processing, some 530 tanneries of varying sizes are distributed throughout the urban and suburban areas (Chilton *et al.*, 1998). These use varying and largely unknown amounts of processing chemicals including chromium salts and solvents, and discharge polluting wastes. Some discharge their polluting wastewaters into the urban sewer network, and some directly to the ground. Separate collection and treatment of the chromium-rich and highly saline effluent from these dispersed, small-scale industries would be difficult and costly and would require relocation of the tanneries to a designated industrial area. For these and similar small-scale, dispersed industrial and commercial activities, mapping their locations may be feasible, if time-consuming (Zaporozec, 2002). The next step of finding out about the volumes and concentrations of effluents may, however, be much more difficult, not least because the owners and managers may be unwilling to pass on the information if their waste disposal practices are not environmentally sound, or even illegal. In the Barbados case study described at the end of this chapter, it was relatively

easy to locate the few hazardous industries, but very difficult to find out about their actual disposal practices because most were probably discharging effluents directly into the underlying coral limestone aquifer.

In practice, therefore, experience shows that estimating the amounts of pollutants released is highly problematic for all but the simplest scenarios. Nevertheless, the ideal information requirements outlined above should still guide the pollutant source and load surveying process. They constitute the basis for subsequent detailed investigations of the most important pollutant sources and loads, by inspection of premises, processes and waste disposal practices and the sampling of effluents. The checklists provided in Chapters 9 to 13 address these information requirements.

Intensity of pollution

If the amount of pollutant released into the environment is known or can be estimated, what are the likely pollutant concentrations or faecal indicator or pathogen numbers at the pollutant source? This component, the intensity of pollution, is depicted in Figure 14.5, showing that pollutants from various human activities may be introduced into the environment at a wide range of concentrations, up to many orders of magnitude greater than those that would be acceptable for drinking-water or environmental standards. There is in fact a whole spectrum of occurrence, from industrial spills or traffic accidents in which a completely undiluted pollutant may be released at the surface, to the impact of agriculture and on-site sanitation, which is likely to produce pollutant concentrations in the same range as, or up to 10 or 100 times greater than guideline values. The former is a point source which directly impacts only a very small proportion of the total volume of recharge (Figure 14.5) and is potentially diluted in the larger water volume within the groundwater flow system, whereas the latter may impact a high proportion of the total recharge (Figure 14.5), depending on the land use distribution in the recharge area and the proportion of land that is cultivated and fertilized. The figure also shows that unsewered sanitation will affect an increasing proportion of the recharge as the density of installations increases from rural to suburban and urban areas.

While conceptually helpful, Figure 14.5 is again a simplification of what is actually a rather more complex situation. Firstly, most of the human activity boxes as pollution sources in the figure include several distinct pollutant groups (Table 14.1). As an example, source concentrations of agricultural pesticides in the soil at the time of application may be three or four orders of magnitude greater than guideline values, whereas nitrate would rarely be more than one order of magnitude greater. Similarly for on-site sanitation or leaky sewers, faecal indicator or pathogens at source may range up to several orders of magnitude per 100 ml, whereas initial nitrogen concentrations would be much less excessive. Initial concentrations are high, but subsequent attenuation processes are very active. Secondly, the horizontal scale extends to very high concentrations to accommodate high solubilized concentrations in groundwater adjacent to spillages of NAPL organic compounds that have relatively low WHO guideline values. For other sources, the range of concentrations may encompass the dissolved solute concentration in the very localized recharge water originating from the source. While generally indicating which activities affect only a small part of the catchment recharge but at high or very high concentrations, and which affect more of the recharge

but at more modest concentrations, the figure may not be exactly comparing like with like. Potential polluting activities identified in the situation analysis should be located on Figure 14.5, and their pollution loading potential increases from bottom left to top right.

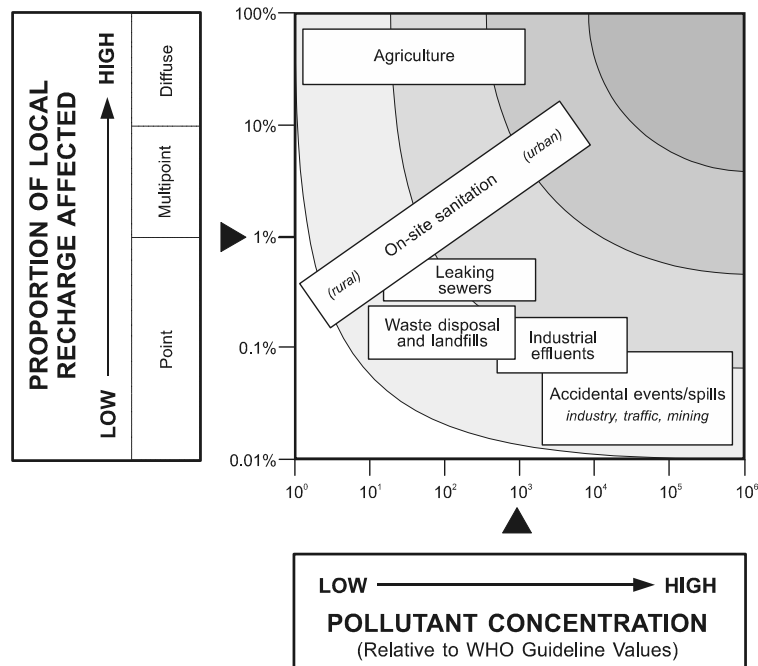


Figure 14.5. Characterization of intensity of pollution (adapted from Foster and Hirata, 1988)

For some diffuse sources of pollution, semi-quantitative estimates of the likely concentrations of persistent pollutants in local recharge may be possible, given many simplifying assumptions (Foster and Hirata, 1988). Approaches to doing this have been developed for chloride and nitrate from unsewered sanitation (Box 14.1) and for nitrate and pesticides from cultivated land (Foster *et al.*, 2002) (see Sections 14.5 and 14.6).

Box 14.1. Estimation of nitrogen loading from unsewered sanitation

Estimates of the possible concentrations of nitrate in the local groundwater recharge in areas of unsewered sanitation can be made for aerobic groundwater systems using the following equation (Foster and Hirata, 1988):

$$C = \frac{1000 \cdot a \cdot A \cdot f}{0.365 \cdot A \cdot U + 10 \cdot I} \quad (\text{Eqn. 14.1})$$

where: C is the concentration in mg/l of nitrate in the recharge (expressed as nitrate-nitrogen), a is the amount in kilograms of nitrogen excreted per person each year, A is the population density in persons/ha, f is the proportion of the excreted nitrogen leached to groundwater (reflects and integrates both the condition of latrines and the vulnerability of underground to nitrogen leaching), U is the non-consumptive portion of total water

usage in l/person/day, i.e. the amount returned to the sanitation system, and I is the natural rate of infiltration for the area in mm/a.

Using this equation Figure 14.6, shows sensitivity of nitrate concentrations in recharge to variations in I , u and f , and indicates that many urban and suburban settings are capable of producing troublesome nitrate concentrations in the underlying groundwater.

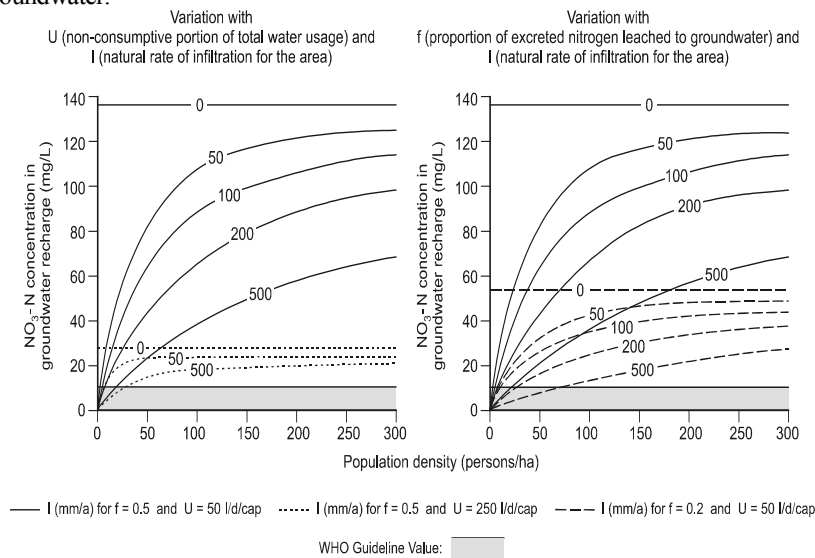


Figure 14.6. Estimation of the potential nitrate-nitrogen load in groundwater recharge in areas of unsewered sanitation (adapted from Foster and Hirata, 1988)

Overall population density and the proportion using unsewered sanitation comes from basic demographic information obtained using the checklist in Chapter 10, and the regional rate of natural infiltration (a proportion of the total rainfall) from the checklist at the end of Chapter 8. The amount of nitrogen produced per person (5 kg) in excreta each year is known from the literature (ARGOSS, 2001). Greatest uncertainty surrounds the proportion of the excreted nitrogen that will be oxidized and leached in the local groundwater recharge. A range of 0.2 to 0.6 is generally considered to be possible in shallow aerobic aquifers (Kimmel, 1984), and the actual proportion depends on the type and condition of installation, the per capita water use, the amount of volatile losses from the nitrogen compounds, the amount of nitrogen removed in cleaning and the geological setting and hydrochemical conditions. In some karstic limestone aquifers, almost all of the nitrogen deposited in sanitation systems may be oxidized and leached. The application of this approach is described in the Barbados case study (Section 14.5).

For high population densities in urban and suburban areas, local infiltration and recharge could be decreased by reductions in permeability in some areas due to surface sealing by built-up areas, and increased in others where collected urban drainage is disposed of to the subsurface, and also increased by leakage from water mains. In mixed areas of sewerred and on-site sanitation, leakage of poor quality water from the sewers may further complicate the estimation.

For most point sources of pollution, the best that can usually be achieved is a relative pollution potential ranking based on the class of pollutants likely to be involved and the possible hydraulic loading, given the major uncertainties about the concentrations of pollutants in industrial effluents, mine waste and landfill leachate and their precise mode of disposition in the subsurface.

Duration of pollution

The final consideration (Figure 14.2) is how long the pollution has been going on for, or is likely to continue. Figure 14.7 provides an indication of the time over which the pollutant load is applied and the likelihood that pollution loading will occur. Thus an accident, spillage or catastrophic leak from a damaged tank may be of very short duration (Figure 14.7) and not penetrate into the subsurface if emergency action to contain the pollutant is taken quickly. If emergency action to deal with accidental pollution is not taken quickly, then solid or liquid pollutants may remain where they were released, either at or below the ground surface, and subsequently be subjected to leaching to groundwater. The slow solubilization of subsurface non-aqueous phase liquid (NAPL) sources, potentially lasting decades, even centuries, is a key concern in this regard. Delays in dealing with accidents thus tend to move such accidental pollution sources upwards and to the right in Figure 14.7.

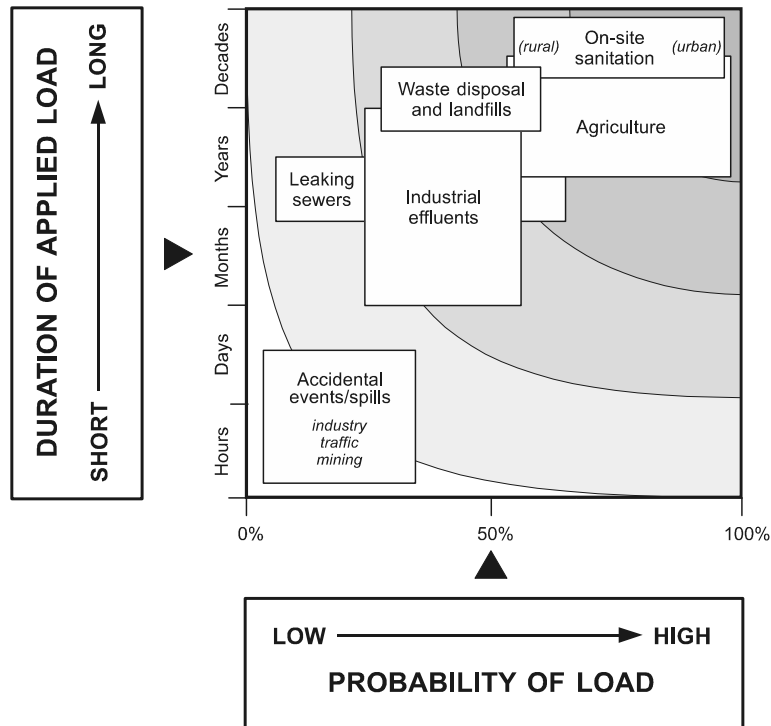


Figure 14.7. Characterization of the duration of contaminant load (adapted from Foster and Hirata, 1988)

Diffuse sources of pollution may also persist for many years or decades and, as in the case of the Perth study (Section 14.6), increase significantly with time as the city has grown and developed. These may be highly likely to cause a pollutant load (Figure 14.7), the magnitude of which will be determined by the characteristics of the other components described above. Thus as for the other components, the pollution potential increases from bottom left to top right.

14.3 OUTCOME OF ASSESSING POLLUTION POTENTIAL

The outcome of assessing the pollution loading potential would be a list of the pollutants expected to reach the aquifer in combination with a semi-quantitative assessment of their respective concentration levels. The process shown in Figure 14.2 provides the information for positioning activities and pollutants on the Y-axis of Figure 14.1. As indicated in Figure 14.1, these then interact in varying and complex ways with the different intrinsic factors used to describe aquifer vulnerability in Chapter 8, and this interaction determines the level of groundwater pollution potential.

The six components of Figure 14.2 each contribute to the overall assessment of pollution loading potential on the right hand side of the figure. The interaction between these components is, however, complex. As an example, if the water table is very close to the ground surface, then unsewered sanitation using pit latrines or septic tanks may enter directly into groundwater, with greatly enhanced likelihood of pollution. Similarly, discharge of highway drainage to soakaways may produce high hydraulic loadings and direct connection to the groundwater, with consequent high pollution potential. This complexity of interaction means that it is conceptually unwise to try to combine them into a single index of overall subsurface pollutant load, and technically difficult to do so. Even where the authors have combined them into a five class qualitative rating scheme (Zaporozec, 2002), they have depicted the intermediate steps in the process so that the dominant factors can be identified. Combined indices can have the result of producing a similar overall ranking for activities and subsurface conditions that are very different, but for which one dominant factor has been largely responsible for the outcome. This is also a concern for vulnerability depiction, and one of the reasons for the debate mentioned in Chapter 8 between those who define aquifer vulnerability in relation to a universal pollutant, and those who would prefer to define vulnerability separately for various classes of pollutant. Combined indices may also mask the components for which control measures would be most effective in reducing pollution potential, i.e. replacing a highly toxic and persistent chemical in an industrial process with a less environmentally threatening compound, or changing the mode of disposition to lessen the potential for pollution to occur.

A further complicating factor is that pollution potential will itself change with time, as human activities at the ground surface change. This is particularly important in the urban and suburban areas illustrated in the two case studies, and it is important to have at least a qualitative indication of both historical and future changes in likely pollution sources. These can affect all of the groups of human activities described in Chapters 9-13; increases in fertilizer use, development of irrigation, new pesticides, replacement of on-

site sanitation with sewerage systems, developing or declining industries, changes in industrial processes, effluent treatment and disposal, closure of mines. Stricter environmental legislation may require responses that in turn also reduce potential pollutant loads. Surveys or inventories to assess the situation and provide the answers to the questions in the checklists are likely to need regular reassessment to confirm their continuing validity, and updating of information where there are major changes.

Changes in pollution loading can lead to major changes in groundwater quality. As an example, long-term increases in the application of nitrogen fertilizers to crops increase the leaching losses, leading to accumulation of nitrogen in the soil and unsaturated zone, and produce widespread upward trends in groundwater nitrate concentrations in many regions of the world (Chapter 9). Abating or reversing trends is often the objective of legislative control, and the withdrawal of the herbicide atrazine for non-agricultural weed control in the United Kingdom in 1992 has produced a reduction in concentrations in some of the public supply sources drawing groundwater polluted by this activity. However, responses of observed groundwater quality to changes in pollutant load are often delayed because of the slow movement of water and pollutants along the groundwater pathway. Further, in the case of removal or reduction of a pollution source at the ground surface, there may be significant amounts of pollutant accumulated in the unsaturated zone en route to groundwater. Pollutant concentrations in groundwater may continue to rise long after the source has been removed, and reversal of the trend may not occur for many years. This situation is seen at other groundwater supply sources affected by atrazine pollution from non-agricultural usage.

Where specific pollutants can originate from more than one major human activity, determining their origin is desirable, otherwise protection and control measures may be directed at the wrong source and hence be apparently ineffective. The most important of these are probably chloride and nitrate, which can be derived from leaking sewers, landfills, unsewered sanitation, livestock farming and agricultural fertilizers. High chloride concentrations may also indicate saline intrusion in coastal areas or the use of salt for road de-icing in cold climates. These pollutants can thus be indicators of impact from both rural and urban activities. Nitrate in particular can be problematic, as unsewered sanitation and agriculture often occur in close proximity. This situation occurs in both case studies and is common in many locations. Because of its importance for drinking-water quality, the nitrate needs to be traced back to its source so that control measures can be correctly targeted. A method that has been successfully applied is to use the distinctive isotopic signatures of nitrogen from animal and human excreta and from inorganic fertilizers to characterize the nitrate observed in the groundwater (Heaton, 1986; Aravena *et al.*, 1993; Exner and Spalding, 1994; Rivers *et al.*, 1996), and hence its origin. The distinctions are not, however, always unambiguous as denitrification can also modify the isotopic signature of the nitrate in groundwater. Alternatively, trace elements associated with high groundwater nitrate concentrations, such as zinc and boron, or pharmaceuticals, may be indicative of a sewage rather than an agricultural source (Lerner and Barrett, 1996).

Where an observed or anticipated pollutant may have originated from numerous small sources as, for example, in a large industrialized city, especially one with a long and complex industrial history, then it is likely to be technically difficult and

unrealistically expensive to determine the precise origins, locations and characteristics of pollution sources (Rivett *et al.*, 1990; Ford and Tellam, 1994). In such circumstances efforts are better directed at protection and control of all potentially hazardous sources rather than trying to prove the precise origins of the pollution.

14.4 USING GROUNDWATER QUALITY MONITORING TO SUPPORT THE ASSESSMENT

A qualitative categorization of pollutant loading is an essential element of assessing pollution potential and ultimately the urgency of management responses to protect public health. Evidence of pollution from any existing groundwater quality data is highly valuable to support, confirm or validate the assessment of pollution potential, and where such data are available, they should always be used. In Perth, Australia, (Section 14.6) groundwater quality monitoring data have existed for many years, and in Barbados (Section 14.5) groundwater quality monitoring was established to complement the assessment of pollution potential. The role of groundwater quality data in relation to other sources of information is discussed in more detail in Chapter 6.

In some circumstances, however, groundwater quality data become highly significant or even essential for risk assessment and management decisions, i.e. where assessment of pollution potential proves to be difficult or inconclusive. This could arise if vulnerability is uncertain due to a lack of essential components of the data specified in Chapter 8, or if pollutant loading is very difficult to assess because there are many, small, dispersed or superimposed sources whose types and amounts of pollutants are unknown. The latter situation will often be encountered in urban and periurban areas in developing countries, where industrial and commercial activities are widely dispersed and individually small, informal or unregistered and extremely difficult to assess, as was the experience in the Barbados case study summarized below.

If there are no groundwater quality data and an inventory of pollution sources proves too difficult or inconclusive, then some selective groundwater quality sampling and analysis from existing abstraction sources can help to provide a rapid assessment of pollution potential. If such a preliminary reconnaissance survey shows evidence of serious pollution, then human resources will need to be made available to start characterizing the main pollutant sources. There is in fact a close link between assessing pollution potential and monitoring, as preliminary surveys of groundwater quality and pollution sources are both important to assist parameter selection in the establishment of long-term routine groundwater quality monitoring programmes (Chapman, 1996; UNECE, 2000).

14.5 THE BARBADOS CASE STUDY

The small but densely populated Caribbean island of Barbados is almost totally dependent on groundwater for public water supply to the resident population and large numbers of visiting tourists. The groundwater resources of such island communities are often limited and of high value, the need for protection is readily apparent and degradation of the groundwater quality would have serious implications, as alternative

supply options are limited and/or very costly. Although the study was undertaken from 1987-1992, it can still be used to illustrate both the assessment of pollution potential outlined in this chapter, and the approaches to and results of the assessment of information needs in Section II.

Existing groundwater protection measures and the reasons for the study

The vulnerability of the coral limestone aquifer of Barbados has long been recognized. To protect the bacteriological and chemical quality of groundwater used for public supply, the Barbados government established a policy of Development Control Zoning around existing and proposed public supply sources in 1963. Five zones were delineated (Figure 14.8) based on a simplified estimation of pollutant travel time through the aquifer. A travel time of 300 days for Zone 1 was selected to be significantly greater than the subsurface survival time of enteric bacteria, and a 600-day travel time was selected for Zone 2. Controls on potential pollution sources such as soakaway pits and septic tanks for domestic and industrial wastewater, fuel storage and industrial development are imposed within the zones (Table 14.2). In 1963, this was an important and farsighted piece of legislation, representing one of the earliest examples of a groundwater protection policy. However, there had been little or no groundwater quality monitoring since its introduction from which the effectiveness of the zoning could be evaluated, and this was a principal objective of the study.

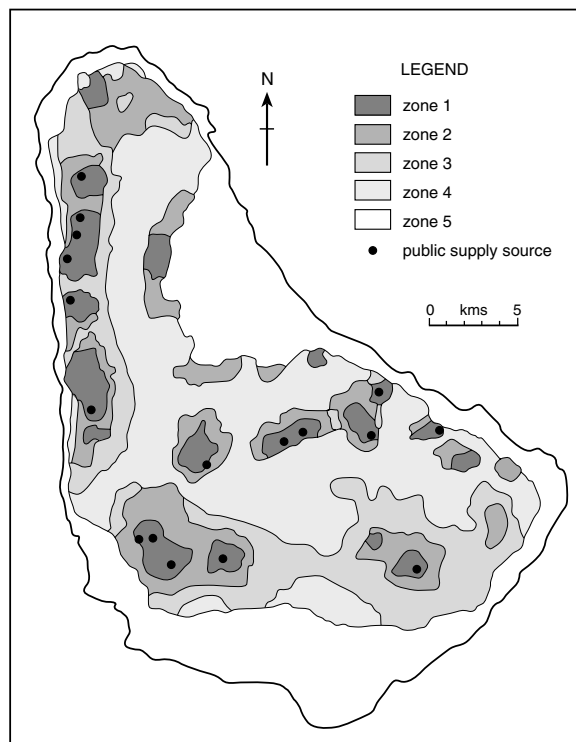


Figure 14.8. Control zones in Barbados (Chilton *et al.*, 2000)

Table 14.2. Principal features of development control zone policy (modified from Chilton *et al.*, 1991)

Zone	Definition of outer boundary	Maximum depth of soakaways	Domestic controls	Industrial controls
1	300 day travel time	None allowed	No new housing or water connections. No changes to existing wastewater disposal except when Water Authority secures improvements	No new industrial development
2	600 day travel time	6.5 m	Septic tank of approved design, discharge to soakaway pits. Separate soakaway pits for toilet effluent and other domestic wastewater. No storm run-off to sewage soakaway pits. No new petrol or fuel oil tanks	All liquid industrial wastes to be dealt with as specified by Water Authority.
3	5-6 year travel time	13 m	As above for domestic wastewater. Petrol or fuel oil tanks of approved leak proof design	Maximum soakaway pit depths as for domestic waste (column 3)
4	All high land	No limit	No restrictions on domestic wastewater disposal. Petrol or fuel oil tanks of approved leak proof design	
5	Coastline	No limit	No restrictions on domestic wastewater disposal. Siting of new fuel storage tanks subject to approval of Water Authority	

Drinking-water Supply

Barbados covers about 430 km² and its population is stable at about 250 000. The overall population density is 6/ha, but ranges from 30/ha in the urban southern and western coastal areas to 4/ha in the rural areas (Chilton *et al.*, 1991). At the time of the study, seventeen large abstraction wells operated by the Barbados Water Authority supplied about 115 ml/d and more than 95 per cent of the population were connected to mains water supply. Only a small proportion, mostly along the southern coastal area, had mains sewerage, although the development and extent of mains sewerage has increased since the time of the study. There were a few private wells, but many are no longer in regular use and the remainder were used for irrigation. The small number of public supply wells helped to facilitate the drinking-water catchment protection policy outlined above.

Groundwater conditions

The coral limestone forms a highly productive aquifer about 100 m thick, which contains a freshwater lens up to about 25 m thick, but thinning to 3 m close to the coast. The permeable nature of the aquifer is demonstrated by the almost total absence of surface drainage and the presence of karstic caves. As is typical for such coral limestones, soils are thin and were expected to provide little protective cover. Perusal of soils data and discussion with local agriculturalists indicated, however, that because of the frequent volcanic activity in the Caribbean region, soils are better developed, thicker and with more clay than might have been anticipated. As a consequence, the whole surface of the limestone aquifer was considered to have high, but not extreme, vulnerability to pollution (Figure 14.1). This somewhat simplified the assessment of pollution potential, as there was no requirement for defining and mapping vulnerability within the study, which therefore concentrated on the Y-axis of Figure 14.1 and the questions in Figure 14.2.

Annual rainfall varies from 1200 mm/yr at the coast to 2200 mm/yr in the interior, providing an equivalent range of some 250-650 mm/yr of recharge. The high annual recharge is roughly equal to the total groundwater storage of this relatively small aquifer. This is an uncommon feature, and implies short residence times and rapid groundwater renewal. Given the lack of surface streams, defining the groundwater catchments was not easy, and the imprecise boundaries followed the rather poorly defined surface watersheds and the buried topography of the coral limestone aquifer.

Approach to the assessment of pollution potential

The study comprised assessments of likely pollution sources in the Belle and Hampton drinking-water catchments, which together provided 90 per cent of the public water supplies of the island, and cover 55 and 67 km² respectively. The work was undertaken primarily by the Barbados Ministry of Health's EED, with technical support from the BGS funded by DFID and the Caribbean Programme Office of the Pan American Health Organization. The results of the assessment for Barbados are summarized in Table 14.3 by giving the qualitative and semi-quantitative responses to the questions in Figure 14.2.

In such a small and intensively developed island, pollution threats could be expected from urban, industrial and agricultural activities (Table 14.1). That these three were likely to be important enough to warrant detailed investigation was apparent from the first reconnaissance drive through the catchments, which indicated the range of urban, suburban and rural population densities, the dominance of sugarcane cultivation supplemented by horticulture and the wide variety and distribution of small-scale industries. Using Table 14.1, pathogens, nitrate from fertilizer and sanitation, agricultural pesticides and salinity were readily identified as potential pollutants requiring further assessment incorporating the components outlined in Figure 14.2.

To evaluate the likely impact of human habitations, information about population distribution, sanitation coverage and types was obtained by the Environmental Engineering Division (EED) project team from existing census data and from the records of the Public Health Inspectorate. For industry, an initial survey used the yellow pages business section of the local telephone directory to identify industrial and commercial premises in the catchments. These were each visited by the EED team, using a questionnaire to obtain information about the industrial chemicals and processes used and the methods of waste disposal. A second detailed survey of the farms and estates in both catchments also used questionnaires and follow-up site visits, to determine cultivation practices, cropping regimes, fertilizer applications and pesticide usage. Support in the design and interpretation of the agricultural survey was provided by staff of the Agriculture Department and of the Government Analytical Laboratory. For both the industrial and agricultural surveys, many additional sources of information – other government departments, universities and the National Oil Company, for example, were consulted, emphasizing that even in relatively small catchments such as these, complex land use and human activity means that the inputs of many technical disciplines are needed and a wide range of institutions are likely to have useful information. Being relatively small catchments, there were no problems related to differences between hydrological and administrative boundaries, and being a small island community, inter-institutional awareness, knowledge and cooperation were fortunately good.

Table 14.3. Assessment of pollutant loading potential for Barbados

Activity (Table 14.1)	Pollutant (Table 14.1)	Component of pollutant loading				Overall outcome	Aquifer vulnerability (Chapter 8)	Pollution potential (Figure 14.1)	Observed concentrations in groundwater
		Pollutant mobili- ty and persistence (Figure 14.3)	Mode of disposition (Figure 14.4)	Quantity of pollutant (Section II)	Intensity of pollution (Figure 14.5)	Duration of application (Figure 14.7)			
Agriculture: <i>cultivation with agrochemicals</i>	Nitrate	High to extreme, mobile and persistent in aerobic limestone	Negligible to low, but with some increased loading by supplementary irrigation of vegetables	Fertilizer applica- tions to sugarcane 130 kg N/ha/yr, but leaching losses known only from literature; horticul- ture variable, but probably higher	Low to moderate, estimated nitrate concentrations of 1-3 times WHO GV in recharge to 35-50% of catchment land	High to extreme, sugarcane long- established and horticulture increasing	High	High	4-8 mg NO ₃ -N/l, but after dilution with recharge from non- cultivated land
	Pesticides	Low to moderate based on properties of com-pounds used (Chapter 4)	Negligible to low (as above)	Herbicide applica- tions of up to 2 kg/ha obtained from surveys; insecticide appli- cations low and selectively targeted	Low to moderate, concentrations of 10- 100 times WHO GV, depending on proportion leached	High overall, but individual com- pounds used for varying times	High	Moderate to high, depend- ing on com-pound	Atrazine always present at low concentrations and up to 3 µg/l

Activity (Table 14.1)	Pollutant (Table 14.1)	Component of pollutant loading					Aquifer vulnerability (Chapter 8)	Pollution potential (Figure 14.1)	Observed concentrations in groundwater
		Pollutant mobili- ty and persistence (Figure 14.3)	Mode of disposition (Figure 14.4)	Quantity of pollutant (Section II)	Intensity of pollution (Figure 14.5)	Duration of application (Figure 14.7)			
On-site sanitation	Nitrate	High to extreme	Low (rural) to moderate (urban), but use of soakaways increases potential	5 kg per person, 4 persons/ha (rural) and 30 persons/ha (urban)	Negligible to low, concentrations in local recharge could be up to 5 times WHO GV	High to extreme	Low (rural) to moderate (urban)	Low to Mode- rate 4-8 NO ₃ -N/l in rural areas, up to 15 NO ₃ -N/l in densest urban areas	
	Pathogens	Low to moderate	Low to moderate (as above)	Unknown	Low to moderate	High to extreme	Moderate to high	Moderate Up to 50% posi- tives <i>E. coli</i> and up to 5 x 10 ² max./100 ml	
Industry: <i>land and well disposal of effluent</i>	Solvents	Low to moderate	Low, but becoming high with disposal in old wells	Small amounts used by small industries, but unable to quantify	Low to moderate, but could not estimate likely concentrations	Low to moderate, usage not long established or continuous	Low	None found in limited sampling	
Solid waste disposal	Metals	Low	Low, small shallow landfills	Mostly household waste with little industrial component	Probably low	Moderate, landfills: long- established, some now unused	Low	Limited monitoring confirms low concentrations	
Traffic: <i>accidental spills</i>	Aromatic hydrocarbons	Low to moderate	Moderate to high, roads drained to soakaways	Regular and frequent transport of unrefined oil by road from oilfield to port	Low to moderate	Low, well- established contingency to clear roads quickly	Low	No monitoring	

Potential pollution threats identified and evidence of impact

The survey results were compiled in spreadsheets and plotted in map form for both catchments, and the map of potential pollution threats for the Belle catchment is shown in Figure 14.9. Potential for groundwater pollution from all three major categories of activity were identified and pollution loadings estimated for unsewered sanitation (Box 14.1) and fertilizer usage. Thus the high density of unsewered sanitation in the urban part of the Belle catchment compared to the rural parts of both catchments presented a threat of nitrate and microbial pollution, which was confirmed by the results of the associated groundwater quality monitoring. Some industries, such as dry cleaning, paint distribution and photographic processing, were identified as using hazardous chemicals and disposing of small volumes of untreated effluents directly into the coral limestone aquifer. The mode of disposition of these small amounts of industrial effluents into soakaways or old wells thus provided a notably high potential to pollute groundwater (Figure 14.4 and Table 14.3). However, they were few, widely dispersed and of very small scale, and no significant impact was detected on groundwater quality in the associated sampling programme. The most widespread and likely threats from industrial and commercial premises were presented by fuel stations and by small vehicle repair workshops.

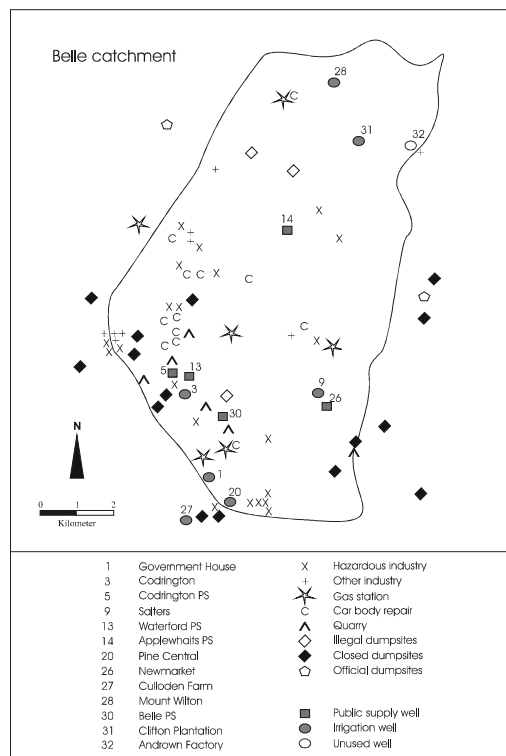


Figure 14.9. Potential pollution sources in the Belle catchment, Barbados (adapted from Chilton *et al.*, 2000)

The agricultural survey highlighted a move away from traditional cultivation of sugarcane to much more varied cropping, especially horticulture. Sugarcane is an efficient user of nitrogen fertilizer as it grows continuously, but vegetables and flowers have shorter growing seasons and are often less efficient users of soil nitrogen. They are also often grown in Barbados with supplementary irrigation, and for these two reasons higher nitrogen leaching may be expected (Figure 14.4). Groundwater nitrate concentrations of 4-8 mg NO₃-N/l were observed everywhere in the rural areas of both catchments, indicating universal but modest impact from agriculture, but there was no evidence of an overall increasing trend during the five years of the study or indeed when the results of the continuing groundwater quality monitoring programme were reviewed later by Chilton *et al.* (2000).

Estimates of nitrate concentrations in recharge reflecting the nitrogen loading from on-site sanitation were made as shown in Table 14.4, using the equation given in Box 14.1. The annual recharge is known to be higher over the hilly rural interior than at the more urbanized southern coastal belt, and per capita wastewater generation is assumed to be slightly lower in the rural areas that are, nevertheless, largely connected to the mains water system. Observed nitrate groundwater concentrations support these estimations, remaining in the range 4-8 mg NO₃-N/l in the whole of Hampton and the northern part of Belle and only rising above 10 mg NO₃-N/l in the southern, urban part of the Belle catchment with the superimposed nitrogen loading from the more dense on-site sanitation facilities (Chilton *et al.*, 1991; 2000). Sampling for faecal coliforms at the same wells supports this interpretation, with more frequent and higher counts broadly correlating with the higher nitrate concentrations.

Table 14.4. Estimated nitrate concentration in recharge affected by on-site sanitation

Components of mass balance calculation:	Urban (Belle)	Rural (Belle and Hampton)
$C = \frac{1000 \cdot a \cdot A \cdot f}{0.365 \cdot A \cdot U + 10 \cdot I}$		
a Nitrogen load (kg N/person/year)	5	5
A Population density (persons/ha)	31	4
F Proportion of nitrogen leached	0.6	0.6
U Per capita wastewater generation (l/d)	250	200
I Annual recharge (mm/yr)	300	500
C Concentration in recharge (mg/l NO ₃ -N)	16	2-3
Range of observed nitrate concentrations (mg/l NO ₃ -N)	4-10	4-8

Horticulture has a much greater variety of pests associated with it than sugarcane – and hence a wider range of herbicides and insecticides are used in their cultivation. A combination of pesticide usage data and published physicochemical properties – solubility in water, persistence as defined by soil half-lives and mobility from partition coefficients (Chapter 4) – was used to estimate susceptibility to leaching to groundwater and hence to select pesticides for monitoring. Pesticide sampling in the monitoring programme detected the almost ubiquitous presence of atrazine, but at low concentrations. This is one of the herbicides most widely used in sugarcane cultivation, but there was little evidence of the main insecticides used. This probably resulted from the wider area (of sugarcane) to which atrazine is applied, compared to the more limited

areas of horticulture, and from the mode of application. Atrazine is a soil-applied herbicide, whereas most of the insecticides are foliar (applied to the plants themselves) and the former is thus more likely to be leached to groundwater.

During the assessment, additional potential pollution sources in the form of poorly maintained oil wells, illegal dumping of solid waste and highway drainage became apparent from visual inspection of the catchments, conversations with residents and organizations. In particular, transport by road tanker of crude oil from the oilfield to the port terminal presented a hazard of traffic accident, spillage and drainage directly into the coral limestone aquifer.

Outcome of the assessment of pollution potential

The assessment successfully identified the main potential pollution sources from urban domestic waste disposal and agricultural activities (Table 14.3). As the whole of the aquifer outcrop is considered to have high vulnerability, the outcome of the pollution loading assessment translates to a position on the Y-axis of Figure 14.1 and thence a ranking of groundwater pollution potential (Table 14.3). The associated monitoring programme established in the study has confirmed that elevated concentrations of nitrate and pesticides do result. Although they occasionally exceed guideline concentrations in private wells, they are lower in public supply wells. The Development Control Zone policy appeared to have been successful in protecting the island's groundwater, which had remained of good quality in spite of the dense population and rapid development. It was recommended from the results of the study that the Development Control Zone policy should not be relaxed, despite pressure from housing and industrial developers, and that the assessment should be extended to the remaining catchments along the island's west coast. It was, however, difficult to evaluate the bacteriological impact from simple monitoring because the public supply sources were equipped with in-well chlorination that prevented collection of pre-chlorination samples. More costly purpose-built sampling boreholes within the control zones would be needed for this.

The Barbados case study can also be used to illustrate key features of the situation analysis from the chapters and associated checklists in Section II (Table 14.5).

While the development control zone policy had clearly served Barbados well, the study identified the main threats, and highlighted the need for continuing vigilance to protect the island's groundwater. Management priorities identified in the study are shown in Table 14.5. While the resident population is unlikely to grow, water demand probably will, partly to meet the growing tourism industry, and this may bring land use changes, such as more golf courses and increasing local demand for horticultural products. Since the study, waterborne sewage has been extended to significant parts of the centre of Bridgetown and the southern coast. This helps protect the coastal zone by reducing pollutant loading to the groundwater discharging to the sea. Waterborne sewage may also need to be targeted at areas where housing is encroaching into the development control zones. This means that, to keep pace with changing circumstances, the situation analysis and pollution potential assessment should be updated, probably on a five-yearly basis. A further recommendation was that the assessment of pollution potential should be extended to the catchments of the wells along the west coast (Figure 14.8).

Table 14.5. Key features of the situation analysis for the Barbados catchments

Component	Key features	Specific difficulties
Collecting information (Chapter 6)	Relatively few institutional stakeholders, and good communication and cooperation between them	EED staff had many other tasks: difficult to find time for survey work
Socioeconomic setting (Chapter 7)	Dense population, relatively high economic status and relatively high environmental awareness	Increasing water demand and high per capita consumption
Hydrogeology, vulnerability and susceptibility to abstraction (Chapter 8)	Whole aquifer/catchment vulnerable: no need for vulnerability mapping Small island, thin freshwater lens, possibility of saline intrusion Large public supply wells with protection zones	Defining catchment boundaries in absence of surface waters
Agriculture (Chapter 9)	Trend from sugarcane to horticulture – increasing range of pesticides	None, good data on crops, fertilizer and pesticide use
Human excreta and sanitation (Chapter 10)	Large difference in housing density between rural and urban areas, significant loading from the latter Easy to distinguish the few sewered areas at the coast from the larger and separate unsewered areas	None, good data for population density and water usage
Industry (Chapter 11)	Small-scale and widely dispersed, mostly commercial and light industry Little usage of potentially polluting materials, but sometimes with poor effluent handling	Easy to map industrial and commercial premises and obtain information on types of pollutant, but very difficult to obtain effluent types, amounts and disposal methods
Waste disposal (Chapter 12)	Small landfills for domestic waste in old quarries	Some former landfills with unknown contents, but outside the study catchments
Traffic (Chapter 13)	Pollution potential evident, particularly during road transport of oil to the port terminal	
Existing water quality data (Chapter 14)	Almost none: groundwater quality monitoring established as part of the study	Good local analytical facilities but some staff constraints for sampling due to other EED tasks
Establishing groundwater management priorities (Chapter 15)	Recommended that controls should not be relaxed despite development pressures Continued assessment of agricultural activity as crops are changing: potential for increase of nitrate and/or pesticide pollution from horticulture, some with irrigation Better implementation of good practice for handling, treating and disposing of industrial effluents Better implementation of good practice for oil transport and traffic accident responses Extend sewage collection in the most densely populated areas Abstraction well controlled to prevent saline intrusion but maintain monitoring of salinity	

14.6 THE PERTH CASE STUDY

Perth is the only large urban centre in Western Australia and is dependent on groundwater for about 70 per cent of all water use, and about 50 per cent of its public supply. Groundwater is pumped from both a regional unconfined aquifer and deep confined aquifers. The latter are well protected and recent initiatives to urbanize their recharge area have been successfully fended off, and the land has remained in government ownership, being used only for a limited amount of forestry. To restrict future development initiatives, discussions on establishing protection zones have been initiated.

The shallow aquifer, however, has been affected by contamination. As the city has expanded, the urban area has encroached on to land in the recharge area which was previously under rural land use or completely undeveloped. The dramatic land use changes which have accompanied the rapid growth of Perth are shown in Figure 14.10. As this is a common situation elsewhere in the world where cities are expanding rapidly, the experience gained in Perth is considered very appropriate as a case study to illustrate how the risks of contamination of groundwater resources important for water supplies can be assessed using the principles outlined in this chapter.

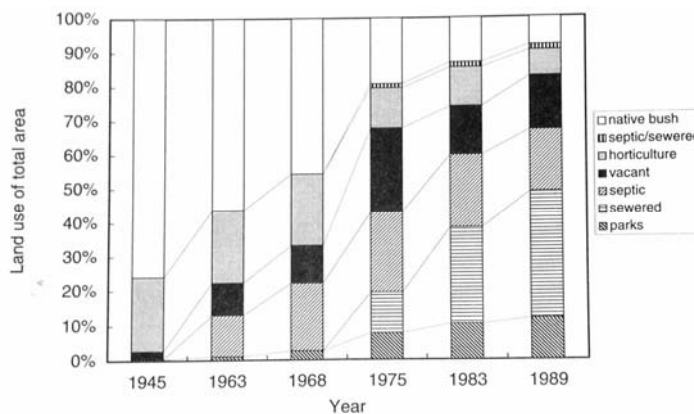


Figure 14.10. Development of land use in the Perth area (adapted from Barber *et al.*, 1996)

Socioeconomic setting

Although it has a population of only 1.3 million, Perth's metropolitan region covers an area equivalent to many large European cities (Figure 14.11). This is because Perth is very much a garden city, with most of the population living in detached houses with large gardens of lawn and exotic shrubs on 500 to 1000 m² blocks. This makes the overall population density (230/km²) lower than the other major cities in Australia and much lower than equivalent cities elsewhere in the world.

Hydrogeological conditions

Fortunately, Perth overlies a very large fresh groundwater resource that forms an important component of the city's water supply and maintains ecosystems around environmentally significant lakes and wetlands. Groundwater occurs in an unconfined

aquifer throughout the region, and in several confined aquifers. The groundwater in storage represents some 500 years of current annual abstraction. Boreholes of up to 1000 m depth supply water with a salinity of only 180 mg/l total dissolved solids (TDS).

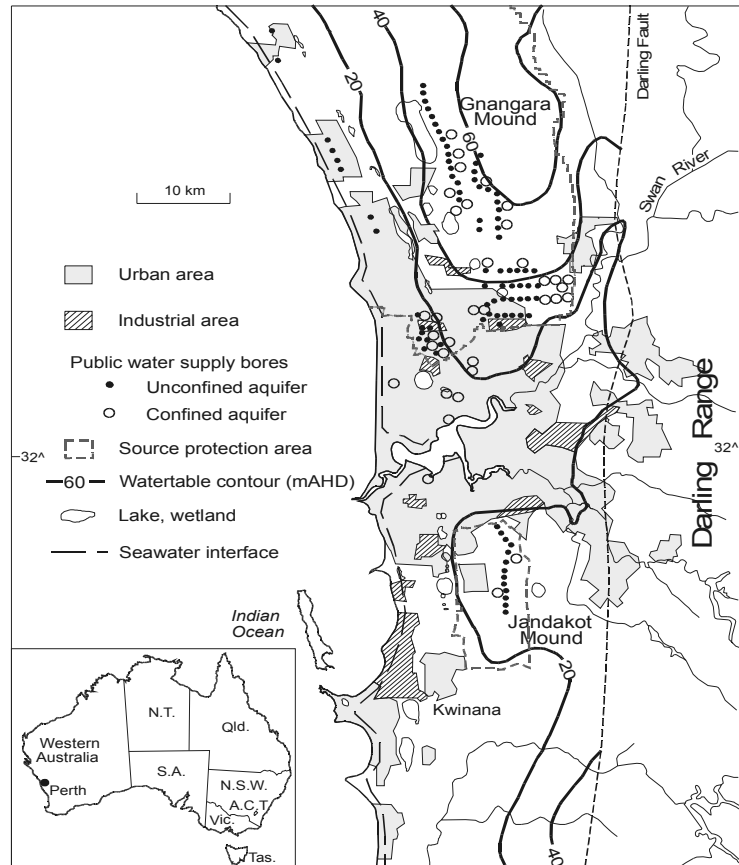


Figure 14.11. Location map of Perth showing major groundwater features

However, the shallow groundwater beneath urban areas is highly vulnerable to pollution owing to the sandy soil and the generally shallow water table, and in some areas pollution has restricted groundwater use and has had an adverse impact on wetlands. Further, the growth of the urban area has overtaken wellfields which were previously located in areas of rural land use, and has compromised water quality.

Water supply situation

The gardens in Perth require watering for about six months of the year because of the region's dry Mediterranean type climate, and are responsible for up to 80 per cent of domestic water use. The shallow water table and unconsolidated sand aquifer mean that groundwater is easily available to most private properties. As a consequence, beside the public water supply wells (mapped in Figure 14.11), there are about 135 000 privately

owned small diameter boreholes or dug wells with spear points, which are used for garden irrigation in Perth. This has greatly reduced the demand from public water supply schemes. The average in-house usage of water of drinking-water quality in Perth is about 120 l/capita/day. Households that do not have access to domestic bores will typically use another 110 l/capita/day of water of drinking-water quality for watering gardens. The application rate of water from domestic bores during summer is of the order of 12 l/day/m²/house.

Impact of urban development on groundwater quality

From Table 14.1, the principal hazards likely to cause groundwater pollution are commercial and industrial point sources within the industrial areas of Perth (Figure 14.11), and widespread but low levels of diffuse pollution from fertilizer use on gardens and from septic tank leachate. The potential point sources of pollution include a range of light industries, petrol service stations and pest control depots (Appleyard, 1995a), which have either accidentally or deliberately disposed of wastes, and about 100 former waste disposal sites (Hirschberg, 1993a; 1993b). Pollution surveys suggest there are about 2000 known or suspected sources of groundwater pollution within the whole region, and contaminant plumes from 100-1000 m or more in length have extended from some of these sites through residential areas where private boreholes are used (Benker *et al.*, 1996). Water quality surveys have detected a wide range of contaminants in shallow private boreholes near many of these sites, commonly at levels that exceed national drinking-water criteria. Although this groundwater is generally not used for drinking, other routes of exposure, such as droplet inhalation or eating irrigated produce have not been thoroughly assessed. Groundwater contamination in at least one private borehole was sufficiently severe to be toxic on prolonged skin contact and to kill plants irrigated with the water (Appleyard, 1995a).

There is also widespread leaching of nitrate from fertilizer use on gardens, and of nitrate, ammonia and bacteria from septic tanks. Estimates of pollutant loading suggest that about 1600 tonnes of nitrogen and 480 tonnes of phosphorus are applied annually to lawn areas in Perth (Sharma *et al.*, 1996). Although much of the phosphorus is bound up in soil profiles, up to 80 per cent of the applied nitrogen may leach to the water table (Sharma *et al.*, 1996). About 160 tonnes of nitrogen are discharged by groundwater to the Swan River each year, and up to 10 tonnes of nitrogen for each kilometre of coastline is discharging annually into the marine environment (Appleyard and Powell, 1998).

Nitrate concentrations in groundwater beneath Perth generally exceed 1 mg/l, and are often greater than 10 mg/l NO₃-N. The nitrate originates from these sources, and concentrations generally increase with the age of urban development (Appleyard, 1995b; Barber *et al.*, 1996). Gerritse *et al.* (1990) estimated that between 80 and 260 kg/ha of nitrogen fertilizer is applied in urban areas of Perth each year, which is comparable to many agricultural application rates. Using these rates as a basis, from their estimate of nitrate loading they suggested that concentrations in groundwater in these areas should be at least 40 mg/l NO₃-N. Observed concentrations are generally much lower, suggesting that significant denitrification must be taking place in the aquifer. The broad scatter of nitrate concentrations in groundwater in urban areas of Perth indicates that denitrification is not occurring uniformly, and/or that nitrogen inputs are not uniformly distributed.

Fertilizer use is particularly high in the horticultural areas located on the fringes of the urban region, as more than one crop is grown per year. Typically, 500-1500 kg/ha of nitrogen (mostly as poultry manure) are applied to crops each year (Lantzke, 1997), and this exceeds the capacity of plants to take up nitrogen by a factor of 4-7 (Pionke *et al.*, 1990). A combination of high intensity (Figure 14.5) and high potential (Figure 14.7) help to make horticulture an activity with high potential for polluting the underlying groundwater (Table 14.6). This reflects the situation in Barbados, where the rapid growth of horticulture was identified as a potential pollution hazard requiring further assessment (Table 14.4), and the presence of intensive horticulture should always be given careful attention in the assessment process outlined in this chapter. As a consequence in Perth excessive nitrate leaching occurs and nitrate concentrations up to 100 mg/l NO₃-N have been observed directly beneath horticultural areas.

Denitrification is favoured where aquifer redox potentials are less than about 300 mV, but there is some evidence that redox potentials increase in the older urban areas in Perth due to the sustained impact of urban recharge processes (Appleyard, 1995b). This may mean that current nitrate concentrations in groundwater beneath urban areas are not sustainable given current fertilizer usage, and that future nitrate concentrations beneath a large part of the Perth metropolitan area will exceed drinking-water guidelines.

A further source of nitrogen as well as faecal pathogen pollution of shallow groundwater beneath Perth is the use of septic tanks. Currently about 25 per cent of the urban area which was mainly developed in the 1950s and 1960s, is unsewered. There is a programme to replace septic tanks with sewer connections, but existing groundwater pollution from this source will take many years to dissipate.

Table 14.6 illustrates how the processes outlined in this chapter can be used to assess the relative hazards that particular pollutants in Perth's groundwater pose to its use as a source of drinking-water. As for Barbados, Table 14.6 provides qualitative and semi-quantitative responses to the questions in Figure 14.2. The assessment provides an indication of the potential magnitude of the loadings posed by a specific pollutant, and on how abundant it is likely to be in groundwater based on land use, aquifer vulnerability and measures of the rate at which the contaminant is discharged to groundwater.

Based on the approach outlined in this chapter, Table 14.6 indicates that the pollutants of most concern in shallow groundwater in Perth are pathogens discharged by septic tanks, high concentrations of nitrate in horticultural areas and benzene concentrations near petrol service stations. This assessment process can then be used to select management strategies to ensure that these pollutant sources do not affect the health of water consumers. This has been done in Perth by establishing drinking-water SPAs and wellhead protection zones where land use can be strictly controlled to minimize the risk of contamination. The risk of contamination from septic tanks is also being managed by progressively installing sewers in the few remaining areas of Perth which are currently unsewered, and the risks of contamination from service stations are being reduced with new codes of practice that require double lined underground storage tanks for fuels with intensive monitoring. A number of measures are also being implemented to reduce nitrate contamination by horticulture. These include training programs for farmers, changing land use in very sensitive areas and requiring farmers to manage their activities according to nutrient management plans.

Table 14.6. Assessment of pollutant loading potential for Perth (shallow aquifer only)

Activity (Table 14.1)	Pollutant (Table 14.1)	Pollutant mobility and persistence (Figure 14.3)	Mode of disposition (Figure 14.4)	Quantity of pollutant (Section II)	Component of pollutant loading (Figure 14.5)	Duration of application (Figure 14.7)	Overall outcome	Aquifer vulnerability (Chapter 8)	Pollution potential (Figure 14.1)	Observed concentrations in groundwater
Gardening: <i>cultivation with agrochemicals</i>	Nitrate	High to extreme, mobile and persistent in shallow sandy aquifer	Negligible to low	1600 tonnes of nitrogen applied annually to lawn areas in Perth (80-260 kg/ha/a with high leaching losses)	Moderate, estimated nitrate concentrations in the range of WHO GV in groundwater and increasing	High, many months per year over decades, increases with age of urban development	Moderate to high	High, in consequence of sandy soils and shallow water table; proximity of activities to some wellfields	High	1-10 mg/l NO ₃ -N often less than estimated, attributed to denitrification in some areas, increase with age of local urban development
	Pesticides	Low to moderate, based on properties of compounds used (Chapter 4)	Negligible to low	Less than 50 tonnes annually at 0.1 kg/ha/a	Low, disperse except when residues poured down drains	Low, intermittent use in summer	Low	Typically <1 µg/l		
Horticulture	Nitrate	High to extreme, mobile and persistent in shallow sandy aquifer	Negligible to low	200-1000 kg/ha of nitrogen applied to multiple crops each year	High to extreme, application rates may exceed plant uptake 4-7-fold	High to extreme, all year	High to extreme	High, in consequence of sandy soils and shallow water table; proximity of activities to some wellfields	High to extreme	Up to 100 mg/l NO ₃ -N
	Pesticides	Low to moderate, based on properties of compounds used (Chapter 4)	Low	0.25-0.5 kg/ha/a	Low to moderate, most degrade in soil	High, used all year	Low to moderate, depending on proper-ties of pesticide	Typically <10 µg/l		

Activity (Table 14.1)	Pollutant (Table 14.1)	Pollutant mobility and persistence (Figure 14.3)	Mode of disposition (Figure 14.4)	Quantity of pollutant (Section II)	Component of pollutant loading (Figure 14.5)	Duration of application (Figure 14.7)	Overall outcome	Aquifer vulnerability (Chapter 8)	Pollution potential (Figure 14.1)	Observed concentrations in groundwater
On-site sanitation: <i>septic tank leachate</i>	Nitrate	High to extreme	Low (rural) to moderate (urban), use of soakaways increases potential which decreases in urban areas with new sewers	5 kg per person, population density 2-3/ha, load 10-15 kg N/ha/a in unsewered areas (25% of total)	Negligible to low, estimated concentrations in local recharge less than WHO GV	High to extreme	Low to moderate		Low to moderate	3-25 mg/NO ₃ -N in urban areas
	Pathogens	Low	As above	Generally low to moderate pathogen loads unless septic tanks poorly constructed and/or badly maintained	Low to moderate	High to extreme	Moderate	High, in consequence of sandy soils and shallow water table; proximity of activities to some wellfields	Moderate, decreasing in urban areas, progressive replacement of septic tanks with sewer connections	Faecal coliforms detected in 25% of boreholes assessed, public warnings to use water for gardens only and not for drinking
Light industry	Solvents, metals, cyanide	Low to moderate	Generally low, but locally high with disposal in wells or in soakaways	Small amounts of solvents used, historically most metal finishing wastes disposed to ground	Low	Low, intermittent usage	Low, mostly historical pollution	High, in consequence of sandy soils and shallow water table; proximity of activities to some wellfields	Low	Limited sampling indicates generally less than solvents 1 µg/l, locally up to 2000 µg/l, toxic metals generally <10 µg/l.

Activity (Table 14.1)	Pollutant (Table 14.1)	Pollutant mobility and persistence (Figure 14.3)	Mode of disposal (Figure 14.4)	Quantity of pollutant (Section II)	Intensity of pollution (Figure 14.5)	Duration of application (Figure 14.7)	Overall outcome	Aquifer vulnerability (Chapter 8)	Pollution potential (Figure 14.1)	Observed concentrations in groundwater
Former waste disposal sites	Metals	Low	Low, small shallow landfills	Mostly household waste with little industrial component	Probably low	Moderate, landfills long-established, some now unused	Low	Low	Low	Limited monitoring confirms low concentrations
Former pest control depots and historical regional pest control	Pesticides	Generally low but locally moderate due to disposal of wastes to ground	Very locally (within 300 m of disposal sites) moderate but generally low	Intermittently applied; historical application of dieldrin to all house pads, fences, wooden poles, etc.	Generally low, diffuse application; high rates at very localized sites	Low, intermittent for modern pesticides, historical use of organochlorine pesticides	Low	High, in consequence of sandy soils and shallow water table; proximity of activities to some wellfields	Generally low, but isolated areas with moderate risk	Generally <1 µg/l, within 300 m of pest control depots generally <10 µg/l
Petrol service stations	Benzene, benzo(a)pyrene	Low to moderate	Moderate to high when water table is shallow due to under-ground leaks without evaporation	Continuous transport of refined hydrocarbons to petrol stations	Moderate to high, most commonly detected industrial contaminants in groundwater	Generally low, but high in zones up to 500 m in direction of flow for service stations	Moderate	activities to some wellfields	Moderate, locally high	Benzene levels generally <1 µg/l, can exceed 100 µg/l up to 500 m in direction of groundwater flow from service stations

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15

Establishing groundwater management priorities

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Management priorities for protecting groundwater will vary widely between settings. Once the pollution potential has been assessed for a given catchment (as discussed in Chapter 14), the priorities for management will depend on the public health burden this pollution is expected to cause currently and in the future. This will determine the urgency with which preventative or rehabilitating management responses are needed.

Management responses will also vary widely, as the feasibility of technically appropriate interventions will depend on the social and economic context in each setting. Also, choices can often be made among a range of responses to a problem, and participatory approaches are likely to lead to different decisions by different communities.

Situation analysis and management decisions for a groundwater catchment need to be based on sound information and on a clear, well-documented decision-making process. Uncertainties and gaps in the information base need to be transparent. This chapter discusses criteria for determining management interventions in relation to their urgency for protecting public health, and in relation to their feasibility for a given catchment.

15.1 ENSURING THE SUITABILITY OF INFORMATION

Establishing a well-documented inventory of all of the available information for a proposed groundwater management area is usually the first step in assessing the pollution risks if groundwater is used as a source of drinking-water. Such an inventory forms the basis of decisions about how potential water quality health risks will be managed. Chapter 6 and the checklists at the ends of Chapters 7-13 provide guidance on what type of information might be included in such a catchment inventory.

Decisions about managing risks to human health usually require the following factors to be addressed to be effective and sustainable (adapted from US Congress Commission, 1997).

- *The decision making process is iterative* – in general, health-risk management decisions need to be periodically reviewed as further information becomes available. An iterative approach helps ensure that management strategies remain up to date with new scientific findings, technological developments, and with national or international best practices.
- *Decision making is participatory* – broad participation with a range of interested or affected parties improves the quality and diversity of opinions that inform the decision-making process. Participation also increases the likelihood that risk management decisions will be accepted and implemented by the relevant parties.
- *Decision making is well-informed* – risk management decisions generally need to be based on information from a variety of sources and on different types of information. Information used may include scientific data, anecdotal records, information about regulatory requirements and socioeconomic information for the region.
- *Decision making is contextual* – management decisions must be appropriate to the social and economic realities of the specific region. Simply adopting practices developed in other parts of the world where there are differences in the level of expertise or available resources to implement management decisions generally does not work. Management practices developed locally are more likely to be sustainable.
- *Decision making is holistic* – focusing management decisions on only one issue may not lead to better health outcomes for communities in the longer term. In general, protecting and managing drinking-water quality should be seen in the context of being one item in a package of measures to protect the health of communities.

Ensuring that information gathered addresses the above factors generally helps prevent many of the pitfalls that often affect decisions made about how drinking-water supplies are managed, particularly the following two:

- crucial information gaps lead to poorly informed decisions which cause resources to be wasted on ineffective measures or even lead to health problems as illustrated in Box 15.1;
- decisions on measures urgently needed to improve public health are sometimes not taken or are unduly postponed because information gaps are used as an excuse for not allocating resources to the measures.

Box 15.1 Cholera Epidemic in Peru in 1991

Andersen (1991) reports that during the 1980s a decision by local water officials to stop chlorinating water pumped from many of the wells in Lima, Peru contributed to more than 300 000 cases of cholera and over 3500 fatalities. The reason given for the decision against disinfection was the perception of a cancer threat from chlorination by-products.

Studies indicating a small statistical lifetime risk of cancer from trihalomethanes and other chlorination by-products were interpreted as demonstrating a more significant health risk than the threat from waterborne pathogens. It is possible that the scale of the epidemic could have been greatly reduced had all of the information about the respective health risks of waterborne pathogens and chlorination by-products been available and understood by the relevant decision makers, and had the relative risk been assessed.

In general, there will always be gaps in the information gathered, and management decisions will often have to be made based on some degree of uncertainty. However, if there are potentially significant risks to human health, the lack of information should not be used as an excuse to delay reasonable and cost effective measures to protect health. If concerns are substantial although the risk level is uncertain, consideration should be given to short-term measures that can be implemented to protect health. This may involve temporary provision of an alternative drinking-water source until the information gaps have been sufficiently closed and the supply demonstrated to be safe, or appropriate control measures have been implemented. In some cases both risks and potential management measures may be self-evident. These generally relate to elements of good environmental practice which can be implemented without the requirement for a detailed pollution potential assessment.

Detecting information gaps during the situation analysis is an iterative process which feeds back into improving the quality of the available information, and helps ensure the inventory is relevant to the local region and water supply. Although obtaining additional information generally requires more investment, it is important to recognize that this effort is usually fairly minor in relation to the resources that may be required to implement some engineered management measures. The additional information may also be important in determining the most cost-effective solution. It is often crucial to be able to convince those responsible for financing management decisions such as funding bodies, government, or donor agencies, to fund such investigations before beginning an activity. This may be facilitated through ongoing consultation with these bodies, and by ensuring that both the information inventory and the criteria used in assessing its value as a basis for selecting management options are well documented and supported by the water consumers.

15.2 PRIORITIZING POLLUTANTS IN GROUNDWATER WITH RESPECT TO URGENCY OF MANAGEMENT RESPONSES

In supply settings where polluted groundwater may affect drinking-water quality, adequate management responses for the protection of public health are required. The determination of their urgency involves a site specific prioritization of individual pollutants in relation to their sources (e.g. polluting activities) on the basis of the following two aspects:

- the extent of the existing groundwater pollution level (e.g. from monitoring data), or the current or predicted groundwater pollution potential of a contaminant in a given setting (as defined in Chapter 14);
- the public health burden, i.e. severity and extent of health consequences.

Management responses for contaminants with the greatest public health burden and the highest pollution level or potential should receive higher priority than those whose health impacts are mild or whose occurrence in groundwater is unlikely. This prioritization approach is conceptually depicted in Figure 15.1.

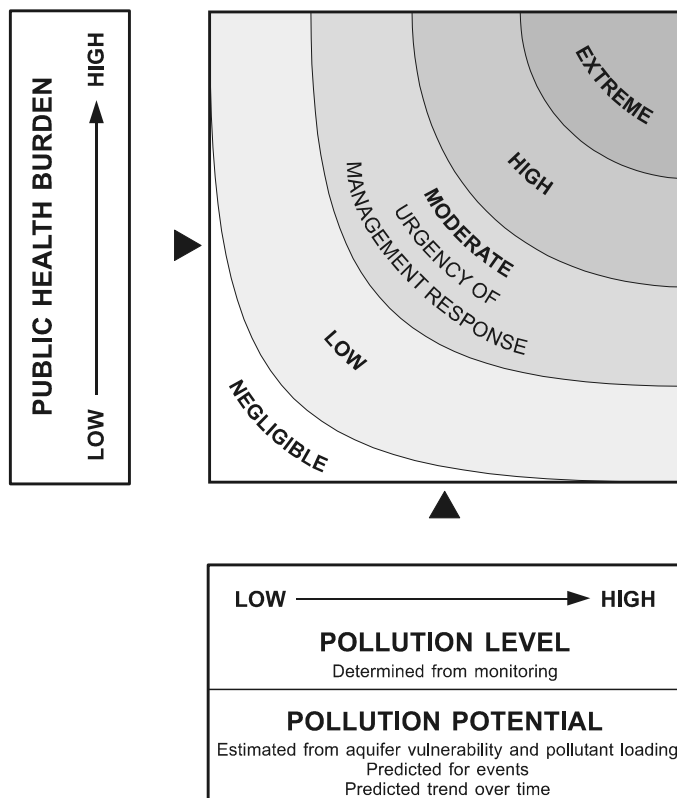


Figure 15.1. Urgency of management responses required to protect public health

The scheme in Figure 15.1 is similar to other risk ranking matrixes commonly used for relating the consequence (e.g. severity and extent) of impacts to the likelihood of an event occurring (WHO, 2004; SGWA, 1998; Deere *et al.*, 2001; MOH NZ, 2001). However, it is different with respect to the role of events causing groundwater pollution: while in general reviewing the likelihood of hazardous events is of crucial importance for risk assessment, groundwater pollution tends to be a more continuous process, e.g. from leaky sewers, poorly sited or designed latrines, waste disposal sites or agricultural activities. Although a pollution event may suddenly occur on the soil surface (e.g. through a tank truck accident or a farmer applying manure), occurrence in the aquifer is often more continuous, and the time pattern with which the pollutant may appear in the aquifer depends on hydraulic loading (i.e. rainfall patterns) as well as on aquifer vulnerability. Nitrate is an example that highlights how discrete contamination events on the surface may lead to continuous contamination of the aquifer.

The pollution potential, as defined in Chapter 14, encompasses both aquifer vulnerability and pollutant loading (in terms of pollutant load and hydraulic load) and thus already includes an assessment of the probability that polluting events on the soil surface result in groundwater contamination. Therefore, for determining the urgency of rehabilitating or preventative management responses, the scale in Figure 15.1 is not event likelihood, but rather pollution potential in terms of the probability of groundwater pollution occurring.

Tables 15.1 and 15.2 give an example of a simple prioritization matrix which applies the general concept of Figure 15.1. The classification scales in Tables 15.1 and 15.2 are based on a qualitative ranking rather than having quantitative values. This reflects the uncertainty of estimating pollution potential and public health burden. Such a ranking scheme therefore has a relative nature: the aim is not a quantification of risk in absolute terms, but to identify the management responses that need to be most urgently addressed.

The approach shown in Figure 15.1 as well as in Tables 15.1 and 15.2 can in principle be expanded to a quantitative or semi-quantitative assessment by reducing uncertainty through improving the knowledge base. For the pollution potential, this would require analyses of the range of contaminants in the groundwater on a regular basis as well as monitoring or modelling of peak concentrations during events and changes over extended time spans to identify trends in order to calculate the dose the population would receive from drinking-water. For the public health burden, the categories for the size of the population affected and the severity of the effect would be calculated and expressed by the concept of Disability Affected Life Years (DALY) as a common public health unit which summarizes all health outcomes caused by a certain disease agent (i.e. chemical or pathogen) and provides an estimate of the burden of disease of this agent (Havelaar and Melse, 2003; WHO, 2004).

For most settings, however, the management of groundwater resources will be substantially improved by a simple approach of setting priorities based on a relative ranking of the urgency of issues as discussed above. Guidance for estimating the pollution potential is provided in some detail in Chapter 14 and in Section II of this monograph. Specifically for chemicals, Thompson *et al.* (in prep.) also provide guidance on deriving priorities for management from the use of chemicals and the conditions in

the catchment. The following will briefly address some general aspects of ranking the public health burden of contaminants which frequently occur in groundwater.

Table 15.1. Simple prioritization scheme: consequence and probability scales (adapted from WHO, 2004; MOH NZ, 2001)

<i>Scale for assessing severity and extent of impacts on public health</i>		
<i>Public health burden (consequence scale)</i>	<i>Description</i>	<i>Position on Y-axis in Figure 15.1</i>
Insignificant	Insignificant	Low
Minor	Minor impact for a small population	↓
Moderate	Minor impact for a big population	
Major	Major impact (potentially lethal) for a small population	
Catastrophic	Major impact (potentially lethal) for big population	High

<i>Scale for assessing the probability of groundwater pollution occurring</i>		
<i>Pollution potential (probability scale)</i>	<i>Description</i>	<i>Position on X-axis in Figure 15.1</i>
Insignificant	Well protected aquifer and insignificant pollutant/hydraulic load	Low
Low	Low aquifer vulnerability and minor pollutant/hydraulic load	↓
Moderate	Low aquifer vulnerability and significant pollutant/hydraulic load	
High	High aquifer vulnerability and significant pollutant/hydraulic load	
Very high	High aquifer vulnerability and substantial pollutant/hydraulic load	High

Table 15.2. Simple prioritization scheme: ranking matrix for determining the urgency of management responses (adapted from WHO, 2004; MOH NZ, 2001)

Pollution potential (probability)	Public health burden (consequence)				
	Insignificant	Minor	Moderate	Major	Catastrophic
Very high	High	High	Extreme	Extreme	Extreme
High	Moderate	High	High	Extreme	Extreme
Moderate	Low	Moderate	High	Extreme	Extreme
Low	Low	Low	Moderate	High	Extreme
Insignificant	Low	Low	Moderate	High	High

Ranking of contaminants according to their public health burden

Ranking microbial and chemical contaminants in groundwater in terms of their public health burden depends to a large extent on site-specific factors, and it is not possible to develop an absolute ranking scale that will fit all cases. However, as a general rule the importance of contaminants in groundwater can be ranked in the following decreasing order:

- waterborne pathogens (Chapter 3);
- naturally occurring groundwater constituents such as fluoride and arsenic (Chapter 4.1);
- nitrate (Chapter 4.2);
- industrial chemicals such as chlorinated or aromatic hydrocarbons (Chapter 4.3), pesticides (Chapter 4.4) or metals (Chapter 4.5);
- pharmaceuticals and endocrine disruptors (Chapter 4.6).

This ranking is indicative only but is typical of both the observed occurrence of contaminants in groundwater and the severity of the health burden that they cause. It can be used as a preliminary ranking if no other site-specific information is available.

Waterborne pathogens pose a much greater *immediate* threat to public health than chemical contaminants and are generally considered to have the highest priority for a management response before chemical contamination issues are considered. In situations where the pollution potential for pathogens is also considered to be high, the implementation of management measures is considered to be extremely urgent (Figure 15.1). Conversely, in situations where the pollution potential is considered to be low (for instance, due to the fact that groundwater is being pumped from a well-constructed deep tubewell in a porous medium aquifer), a management response will be considered to be much less urgent, and addressing other contaminants, such as some accumulating chemical contaminants, might have a higher priority.

As discussed in Chapter 4, fluoride and arsenic in groundwater supplies may have significant effects on public health. These contaminants are generally of natural origin, and in many situations their concentration is low in groundwater. Their presence in health-relevant concentrations in a given groundwater supply depends on local geological factors and on specific hydrochemical conditions (Chapter 8) being present in the aquifer to allow these chemicals to be mobilized from sediments or bedrock into groundwater. Therefore it is essential to specifically address the possible presence of natural groundwater constituents in the catchment-specific situation analysis. This should include undertaking specific sampling and chemical analysis for these constituents, and obtaining information about the local geological conditions to determine whether there is a risk of land use or groundwater pumping increasing the concentrations of fluoride or arsenic in groundwater. This information will help determine where these chemical constituents should plot on the matrix in Figure 15.1.

In some situations, nitrate is of concern to public health because of potential health effects on bottle-fed infants (i.e. metHb, particularly in the presence of simultaneous microbial contamination; see Chapter 4.3), the large inputs of this chemical to groundwater in areas with intensive agriculture and/or on-site wastewater disposal, and its tendency to accumulate in aquifers. The potential health consequences of nitrate contamination will vary depending on the size of the population exposed (which in turn

strongly depends on social factors, i.e. prevalence of breast feeding and parental knowledge) and this will affect where this contaminant will plot on the scheme in Figure 15.1.

With the exception of localized major point sources of contamination, exposure to chemical contaminants such as heavy metals, organic pollutants (e.g. chlorinated or aromatic hydrocarbons), and pesticides through drinking-water is usually a less immediate threat to public health. One aspect is that the major exposure pathways to these substances are usually air pollution and food rather than drinking-water (WHO, 2004). For protecting public health, management of these greater sources of contamination might be more urgent than addressing their occurrence in water. Although implementing management measures to deal with these contaminants is usually less urgent for most groundwater supplies, there may be circumstances in which a situation assessment may indicate the probable presence of very high concentrations in groundwater due to local contamination, raising the management priority of one or more of these chemicals.

Pharmaceuticals, endocrine disruptors and most pesticides rarely occur in groundwater in concentrations that have been shown to be hazardous to human health. In most cases the ranking following Figure 15.1 will therefore result in a rather low urgency for management response. However, in many societies there is increasing concern over traces of pharmaceuticals and pesticides found in groundwater used as drinking-water sources. Such issues may be addressed in the priority setting matrix by including other criteria, such as public perception and value judgements, in addition to public health burden. Where public concern over pharmaceuticals or pesticides makes the headlines, management measures may indeed be ranked as urgent. However, scientifically substantiated assessment of the public health impact will always need to be the most important criterion for setting priorities and for defining the urgency of management responses in order that resources are not diverted from more pressing public health problems.

In summary, the simple ranking scheme presented in Figure 15.1 and in Tables 15.1 and 15.2 is based on the relative likely health burden caused by a number of contaminants, and not their absolute magnitude, and thus simply indicates management priorities. Waterborne pathogens may cause immediate illness and their presence in water requires an urgent management response either in the catchment or at the water supplier's operational level (i.e. treatment). Chemical contaminants usually require long-term exposure to cause health effects. Consequently, management measures for chemicals are of less urgency in most circumstances and measures may be delayed until management responses for the control of pathogen contamination have been implemented.

Assessment of persistent contaminants

Unlike waterborne pathogens, which survive in groundwater for a limited period of time (Chapter 3), some chemical contaminants may persist in groundwater over a long period of time, with little or no attenuation. In situations where there is a continuing source of chemical contamination and the loading rate at which the chemical is leached into groundwater is greater than the rate at which the contaminant is removed by physical,

chemical or biological processes in the aquifer, concentrations of the contaminant in groundwater may progressively accumulate with time.

The most common example of this behaviour is nitrate contamination in groundwater in regions where intensive agriculture is poorly managed. Nitrate concentrations in groundwater in these regions often continue to increase over many decades if appropriate land use management practices are not implemented. Accumulation has also been observed for various industrial chemicals (e.g. chlorinated solvents) and some pesticides (e.g. atrazine).

For such contaminants rehabilitation of groundwater quality is typically difficult and costly, and interventions may be needed before concentrations reach health-relevant levels. The process of prioritizing management responses therefore needs to address the issue of contaminant accumulation by estimating trends or using a prediction of the contaminant concentration in groundwater at some future time if no management action is taken to stop or reduce the polluting activity or practice. An outcome of such an assessment would be to indicate whether the contaminant could become an urgent management priority unless the source of contamination were to be removed or the loading rate greatly reduced. Such an assessment could be used to help set priorities for progressively changing land use within a catchment area to protect groundwater quality in the longer term or to introduce changes such as appropriate chemical handling practices in small or large industries.

Specific advice on predicting long-term nitrate concentrations in groundwater in urban and periurban environments where there is limited information can be found in Lerner (2000) and ARGOSS (2001).

15.3 SELECTION OF MANAGEMENT OPTIONS

The last step in the situation analysis for a groundwater supply is to select possible management options that are appropriate for the magnitude of the health risk posed by a specific contaminant. The range of possible measures for protecting groundwater from becoming polluted through human activities is discussed in some detail in Sections IV and V of this monograph.

Once the urgency of an intervention to protect public health has been determined, apart from the technical adequacy of the measure, selecting effective management options also needs to consider the following aspects:

- delayed response time between management interventions (i.e. removing the contaminant source) and measurable reduction of aquifer pollution;
- barriers in place in addition to groundwater protection (e.g. treatment);
- socioeconomic feasibility of management responses.

Aquifer response time

Aquifers tend to respond only slowly to changes in contaminant loading due to retention processes such as adsorption and desorption to soil particles (see Chapter 4). Moreover, due to slow flow rates and long retention times of water in many aquifers, elevated contaminant concentrations may remain present for many years. This effect has particularly been shown for contamination with chemicals such as nitrate or some

pesticides (e.g. atrazine). For example, the response time between successfully implemented measures targeting the reduction of nitrogen loading from agriculture in the catchment area and measurable reduction of nitrate concentration in groundwater can range between a few years and several decades (Behrendt *et al.*, 2000).

In situations where groundwater used for drinking-water supply is contaminated and where the implementation of management measures is assessed as urgent for protecting public health, the delay in response needs to be taken into consideration. As discussed below, measures in addition to those protecting or rehabilitating the aquifer from polluting activities might be needed (e.g. water treatment, change of source) in order to provide safe drinking-water.

The delay in response is an inherent property of the groundwater system that cannot be changed by any management measure. It is therefore important to recognize that control measures for reducing chemical contamination (e.g. nitrate, pesticides) in groundwater are likely to show results in the long term only and that short-term 'success stories' are rarely achievable. When planning and implementing management actions, this issue needs to be adequately communicated both to communities using the resource for drinking-water supply and to funding agencies and politicians in order to avoid misplaced expectations and disappointment that may impair the political or financial support.

Multiple barriers

Wherever possible during the process of selecting management options, it is important not to select just one measure and rely on it for the long-term protection of public health. In particular, relying on water treatment alone to prevent health problems from contaminated groundwater may be a high-risk management strategy for some contaminants, particularly microbial contaminants. This could have significant public health consequences if the treatment system fails or mistakes are made by the operators of the system and water treatment is ineffective (O'Connor, 2002).

As depicted in Figure 15.2, risks to public health can generally be minimized when a group of complementary management measures are implemented together to ensure that there are several barriers in place between a potential source of contamination and a water consumer, particularly when the contaminant can have a major impact on health. The presence of several barriers means that the overall water supply is protected from a system failure or human error at any one point in the system because there are backup protection measures, and thus the water supply becomes a fail-safe system. This multi-barrier principle is one of the basic principles of drinking-water hygiene (WHO, 2004).

Typical barriers in groundwater supplies include:

- management practices in the catchment area to reduce contaminant inputs from human activities into groundwater (see Chapters 21-25);
- source-water protection through control of land use in protection zones (see Chapter 17);
- adequate design, construction and maintenance of water supply wells (see Chapter 18);
- treatment of pumped groundwater (LeChevalier and Au, 2004);
- ensuring adequate disinfection residual in the water distribution system;
- protection and maintenance of the distribution system (Ainsworth, 2004).

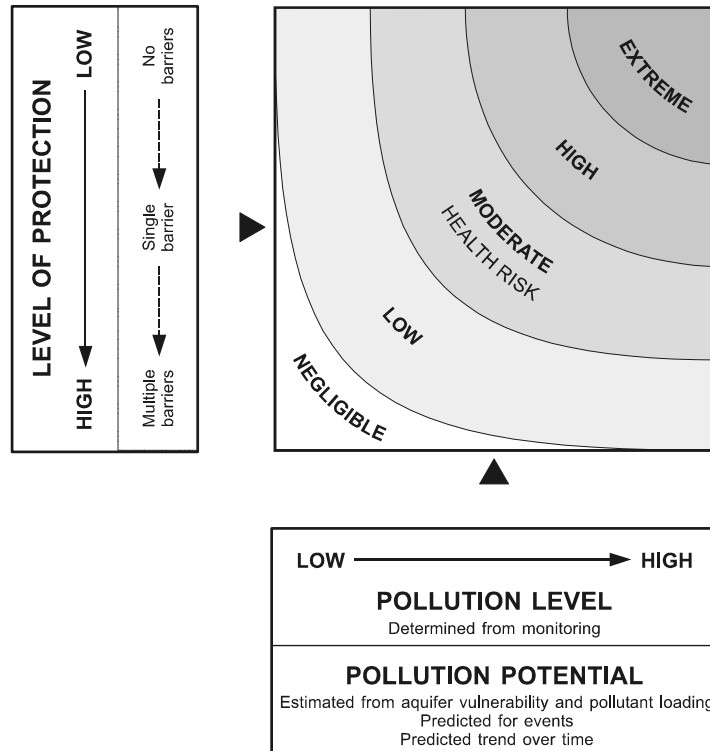


Figure 15.2. Reducing health risks by using multiple barriers to protect a water supply (adapted from Hruday, 2001)

The extent to which these barriers are needed will depend on an assessment of the possible health outcomes of contaminants, the size of the population relying on the water supply, the resources available for management, and an assessment of the costs of implementing management practices against the possible benefits in the specific situation.

Many low-income countries lack the resources or expertise to implement a broad range of groundwater protection measures, and in some countries it can be difficult to convince key political decision makers of the importance of groundwater protection for long-term water safety. In such situations water treatment or the provision of another source of water are important immediate health protection measures.

Socioeconomic feasibility

Groundwater protection measures do not have to be expensive, and small incremental changes over a period of time can greatly improve the quality of groundwater or avoid degradation of quality. Even simple inexpensive measures such as ensuring that defecation is not carried out within 10 m of a water supply well and ensuring that surface run-off is diverted away from the well will significantly reduce public health risks from such a water supply (ARGOSS, 2001; Howard *et al.*, 2003). Other groundwater

protection measures will require investments, e.g. constructing latrines, improving seals on wellheads or improving drainage of roads. Funding for these may or may not be available. Designating protection zones in the immediate vicinity of a wellhead or extended further into the aquifer's catchment may be inexpensive to the authority doing so, but – as discussed in Chapter 5 – can disrupt the livelihoods of inhabitants of the land above the aquifer or can have substantial economic consequences for them. In some settings, though interventions may appear appropriate in theory, institutional capacity is too weak to implement them.

Unless a catchment is largely uninhabited and unused by humans, the aquifer protection measures introduced in Sections IV and V of this monograph will often intervene in the way people are currently doing things, and will work only if the stakeholders in the catchment are willing to make changes. This pertains to land use in general, but also to practices, e.g. in agriculture, sanitation or handling and storing hazardous chemicals. Therefore, while for a given setting the urgency of mitigating or preventing groundwater contamination is determined from an assessment of pollution potential and public health burden (Section 15.2), selecting appropriate management measures requires a further step, i.e. assessing their feasibility in the specific setting. Feasibility depends on a variety of factors, such as cultural values, public perception, education, land tenure rights, socioeconomic status, legal requirements and institutional capacities (see Chapters 5 and 20). These factors need to be evaluated in relation to the management responses envisaged. The result of such an evaluation may be that socioeconomic measures are a crucial part of the management package, equally or even more important than the actual technical measures to protect the aquifer.

As discussed in some detail in Chapter 5, public communication and consultation is not only an important tool for assessing the potential of aquifer pollution and the feasibility of measures suggested by scientists and engineers. Beyond this, participation of the population affected by groundwater protection measures is key to developing approaches that will be supported locally and can therefore be implemented more readily. Where people's livelihoods are positively affected by a protection measure, rather than the measure being perceived as only having a negative impact, particularly in the short term, interventions are more likely to be accepted and maintained. It is important to communicate that increasing costs arise not only from the protection of the resource, but also from its deterioration. In this context, there may be conflicting interests between different stakeholders in the catchment. For example, abandoning a resource and piping in water from a more distant one in order to be able to continue a polluting activity may be in the interest of some, but others who could not afford a more expensive supply would prefer protection. The planning of groundwater protection measures will need to consider how the needs of all stakeholders can best be incorporated into the policy, and how costs can be minimized while maximizing protection.

Figure 15.3 conceptually depicts that both urgency of an intervention and the feasibility in a given setting will determine which type of management action can be taken. Management responses to technically similar problems may be very different between settings, depending on what is locally feasible.

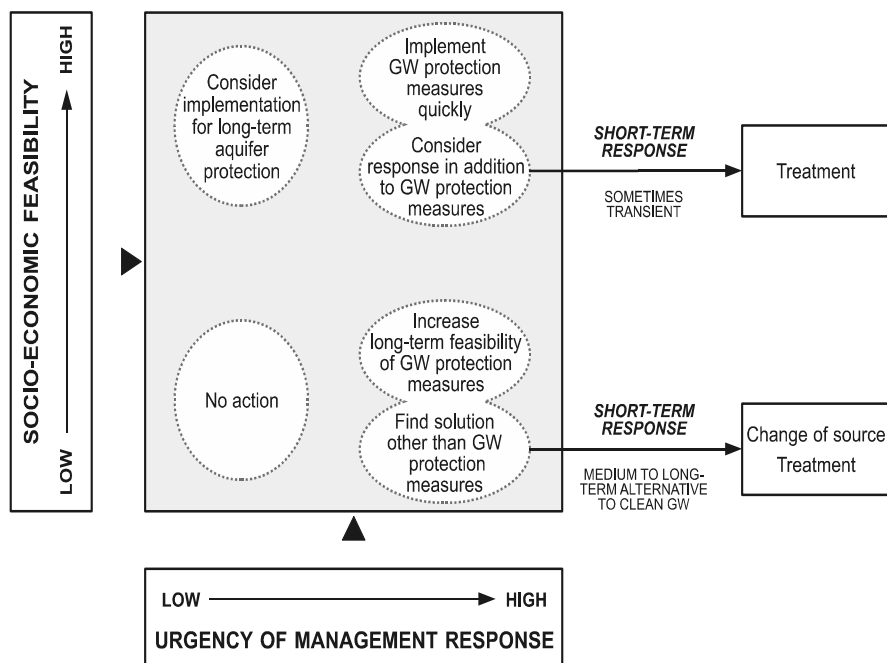


Figure 15.3. Selection of management responses in relation to their urgency and feasibility

The upper right-hand corner of Figure 15.3 shows that where urgent groundwater protection measures are assessed to be feasible, the key management action is their rapid implementation. Additional short-term measures at the point of consumption (e.g. treatment) may be necessary until the groundwater quality shows a response to the protection measure (see example settings A and C in Table 15.3). Where interventions are urgent, but it is not feasible to improve groundwater in the medium term (bottom right-hand corner of Figure 15.3), the primary response to protect public health will be management actions other than groundwater protection, as safe groundwater is not likely to become available in the short term (see example setting B in Table 15.3). However, these tend to involve either use of a more distant source or treatment, both of which are costly. In settings in which an aquifer can still be rehabilitated, an extended process of community consultation and discussion may therefore lead to additional action for groundwater protection or remediation in the longer term. As discussed in Chapter 5, feasibility may be increased by socioeconomic measures such as compensation payments for restrictions on land use, but also by e.g. improving tenure rights to make protection attractive in the longer term.

A different group of situations are those in which management responses against contamination are assessed to be less urgent (see Chapter 15.1). If feasibility is also low (e.g. for protecting an aquifer from low levels of pesticides), no action would be taken other than improving risk communication to the public if there is a concern (bottom left-hand corner of Figure 15.3). However, where measures to prevent such pollution are feasible (upper left-hand corner of Figure 15.3; see example setting E in Table 15.3),

implementing such measures would be appropriate. Such a decision would follow the precautionary principle. Precautionary action is likely to be more feasible in settings in which the public perception values the resource and clean water is a widely accepted goal, and particularly where the overall public health and socioeconomic conditions enable such a priority to be set.

Table 15.3. Examples for the selection of management responses in relation to their urgency and feasibility

Groundwater pollution problem	Urgency	Groundwater protection measure	Feasibility	Alternative and/or supplementary measures
<i>Example setting A</i> with periodic detection of high <i>E. coli</i> counts in poorly constructed wells in a shallow vulnerable aquifer adjacent to an open defecation area	Extreme	Improve construction and maintenance of wells Construct latrines downgradient from wells	High → upper right-hand corner of Figure 15.3	Additional short-term water treatment (e.g. boiling, disinfection)
<i>Example setting B</i> with periodic detection of high <i>E. coli</i> counts in poorly constructed wells in a shallow vulnerable aquifer adjacent to an open defecation area	Extreme	Improve construction and maintenance of wells Construct latrines downgradient from wells	Low → bottom right-hand corner of Figure 15.3	Abandon wells and rebuild in uncontaminated area, or provide alternative water source (e.g. use of water tankers) Public consultation for increasing feasibility of aquifer protection
<i>Example setting C</i> with periodic detection of high <i>E. coli</i> counts from contaminated run-off in poorly constructed wells	High	Ensure setback distances to sources of pollution Improve construction and maintenance of wells	High → upper right-hand corner of Figure 15.3	Public communication about wellhead protection
<i>Example setting D</i> with nitrate contamination from agriculture in properly constructed tubewells	Moderate	Implement control measures for stock density as well as for application of fertilizers and manure	Low → bottom right-hand corner of Figure 15.3	Provide appropriate bottled water for bottle-fed infants; and/or encourage breast feeding
<i>Example setting E</i> with pesticide contamination from agriculture in properly constructed tubewells	Low	Implement training programme for farmers on good practice in choice, application and disposal of pesticides	High → upper left-hand corner of Figure 15.3	Improve risk communication to the public

Management actions for the contaminants ranked as urgent may result in simultaneous remediation of those with a lower urgency ranking, e.g. where nitrate loading from human excreta occurs together with faecal indicators, measures reducing the latter are likely to also reduce the former. Such benefits need to be included in the case for measures that are being proposed.

Generally, where socioeconomic conditions indicate that the availability of financial resources for advanced drinking-water treatment is low, maintaining groundwater quality as a cheap and safe resource not requiring treatment may be particularly important. Under these circumstances it is probable that the situation analysis would identify aquifer and/or wellhead protection as a high priority.

The important exception to the general scheme shown in Figure 15.3 is where groundwater contains toxic natural constituents such as fluoride or arsenic at concentrations that are of health concern. In these situations, groundwater protection measures will not reduce the concentrations of these constituents and water treatment or providing alternative sources of drinking-water are the only effective management options. This does not mean that groundwater protection measures are abandoned in these situations, as other possible contaminants derived from land use will still need to be managed to prevent contamination of the water supply even if it is being treated to remove the natural chemicals such as arsenic or fluoride.

15.4 DOCUMENTATION AND REPORTING

Comprehensive and easily understood documentation of the situation assessment is important as it enables both the decision-making process for a specific supply and the information on which the decisions were made to be clearly communicated to water consumers, regulatory and funding agencies and other stakeholders. In particular, documentation is important for the following reasons:

- Documentation of the sources of information that were used to make management decisions enables the quality of the information to be assessed. This can help identify whether there are any major gaps in the information used which may affect both the assessment of groundwater pollution risks and the measures selected to manage groundwater quality.
- Potential water consumers and the general public have a right to know what potential contamination risks occur in an existing or proposed groundwater supply and about how these risks will be managed. Water consumers need assurance that their water supply will not pose a public health threat, and demand a high level of accountability from water suppliers and government regulatory agencies for decisions made about drinking-water safety (CELA, 2001).
- A report of the results of the groundwater source assessment is a powerful tool to initiate discussions with a wide range of stakeholders about the need to protect the quality of groundwater in a region.
- Good documentation allows decisions about water quality management to be easily evaluated and updated as new information becomes available.

- Good documentation together with ongoing consultation with the community and key decision-makers helps secure funding and community support for implementing groundwater protection measures to ensure that drinking-water will not affect public health.

The whole process of the situation analysis should be documented formally in a report by the situation assessment team. As well as describing the results of the situation analysis and the criteria for decisions made in the assessments, the report should include the technical details such as key persons involved in conducting the situation analysis, when the information was collected, the sources of data (e.g. from site inspection, statistics, government bodies, universities, published/unpublished information), contact persons for information, and the location and format of storage of the information. A key component of this report will often be a series of maps of the catchment area showing the aquifers and groundwater conditions, vulnerability, groundwater supplies, land use and human activities which highlight the major potential sources of groundwater pollution. If possible, these should be in GIS format at a common scale so that they can be easily overlaid and updated.

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