17

Groundwater protection zones

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The protection of groundwater sources used for domestic supply requires actions at both the wellhead (as described in Chapter 18) and the wider aquifer, and they should be closely linked to form a continuum of measures. Unless the groundwater catchment area is under the control of the water supplier, implementing the full suite of measures will require actions by multiple stakeholders and intersectoral collaboration is essential for success.

Many countries have developed and implemented policies for preventing the pollution of groundwaters. These commonly involve regulatory control of activities which generate or use polluting materials, or control of the entry of potential pollutants into vulnerable surface and underground waters. However, protection zones are not applied in all countries, despite a recognition of their desirability (Bannerman, 2000). This may be due to a number of factors, including the lack of sufficiently detailed information regarding the hydrogeological environments (Taylor and Barrett, 1999; Bannerman, 2000), or existing land uses that impede enforcement of such a concept. Furthermore, poverty, uncertain tenure and limited capacity to provide compensation packages suggests that such approaches may be difficult to implement particularly in developing countries.

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Protection zones are particularly effective to control pollution from diffuse sources (e.g. agriculture or traffic), while the prevention or control of point sources of pollution may be achieved through rather straight-forward approaches such as permit systems or other legal controls on the quantity, types of substances and places where discharges may take place. The prevention of groundwater pollution from diffuse sources is more problematic because the sources are less easy to identify and the impact is more difficult to control. Thus effective regulatory control of diffuse pollution often relies upon prohibition or restrictions of polluting activities in specific protected areas where impacts on groundwater sources are likely to be serious.

This chapter provides a review of the concepts of protection zones and provides examples of different ways in which these may be applied. Simple, pragmatic approaches are described as well as more complex approaches involving assessments of vulnerability of the aquifer. The smaller scale approach of well-head protection and sanitary completion in order to prevent contaminant ingress through short-circuiting is discussed in Chapter 18.

NOTE ▶ *This chapter introduces options for controlling risks by implementing protection zones. The information presented here supports defining control measures and their management in the context of developing a Water Safety Plan (Chapter 16).*

Water suppliers and authorities responsible for drinking-water quality will usually have a key role in the definition of control measures involved in the designation and delineation of protection zones, but they will rarely be the only actors responsible for implementation and monitoring. This rather requires close collaboration of the stakeholders involved.

17.1 THE CONCEPT OF A ZONE OF PROTECTION

The concept of a zone of protection for areas containing groundwater has been developed and adopted in a number of countries. Many have developed guidelines for water resource managers who wish to delineate protection areas around drinking-water abstraction points (e.g. Adams and Foster, 1992; NRA, 1992; US EPA, 1993). In general, the degree of restriction becomes less as the distance from the abstraction point increases, but it is common to include the area of the whole aquifer from which the water is derived in one of the zones, and to restrict activities in such areas in order to give general long-term protection.

Commonly, zones are delineated to achieve the following levels of protection:

- A zone immediately adjacent to the site of the well or borehole to prevent rapid ingress of contaminants or damage to the wellhead (often referred to as the wellhead protection zone).

- A zone based on the time expected to be needed for a reduction in pathogen presence to an acceptable level (often referred to as the inner protection zone).
- A zone based on the time expected to be needed for dilution and effective attenuation of slowly degrading substances to an acceptable level (often referred to as the outer protection zone). A further consideration in the delineation of this zone is sometimes also the time needed to identify and implement remedial intervention for persistent contaminants.
- A further, much larger zone sometimes covers the whole of the drinking-water catchment area of a particular abstraction where all water will eventually reach the abstraction point. This is designed to avoid long term degradation of quality.

The number of zones defined to cover these function varies between countries, usually from 2-4. By placing some form of regulatory control on activities taking place on land which overlies vulnerable aquifers, their impact on the quality (and in some cases quantity) of the abstracted water can be minimized. The concept can be applied to currently utilized groundwaters and to unused aquifers which might be needed at some time in the future. Legislation not directly related to pollution prevention, such as those related to planning, industrial production and agriculture, may be used to adjust or limit the extent to which activities that could impact upon the aquifer take place in the protection zone. In order to implement such policies, there must, of course, be adequate supporting legislation available to control these activities. As noted in Chapters 5, 7 and 20 such legislation may need to consider compensation packages to account for potential lost earnings of land users whose activities may be controlled to protect underlying groundwater.

17.2 DELINEATING PROTECTION ZONES

Groundwater protection zones have developed historically, using a variety of concepts and principles. Although some include prioritization schemes for land use, all aim at controlling polluting activities around abstraction points to reduce the potential for contaminants to reach the groundwater that is abstracted. Criteria commonly used for these include the following:

- *Distance*: the measurement of the distance from the abstraction point to the point of concern such as a discharge of effluent or the establishment of a development site.
- *Drawdown*: the extent to which pumping lowers the water table of an unconfined aquifer. This is effectively the zone of influence or cone of depression.
- *Time of travel*: the maximum time it takes for a contaminant to reach the abstraction point.
- *Assimilative capacity*: the degree to which attenuation may occur in the sub-surface to reduce the concentration of contaminants.
- *Flow boundaries*: demarcation of recharge areas or other hydrological features which control groundwater flow.

Approaches using such criteria range from relatively simple methods based on fixed distances, through more complex methods based on travel times and aquifer vulnerability, to sophisticated modelling approaches using log reduction models and contaminant kinetics (Figure 17.1). Uncertainty of the underlying assessment of contamination probability is reduced with increasing complexity.

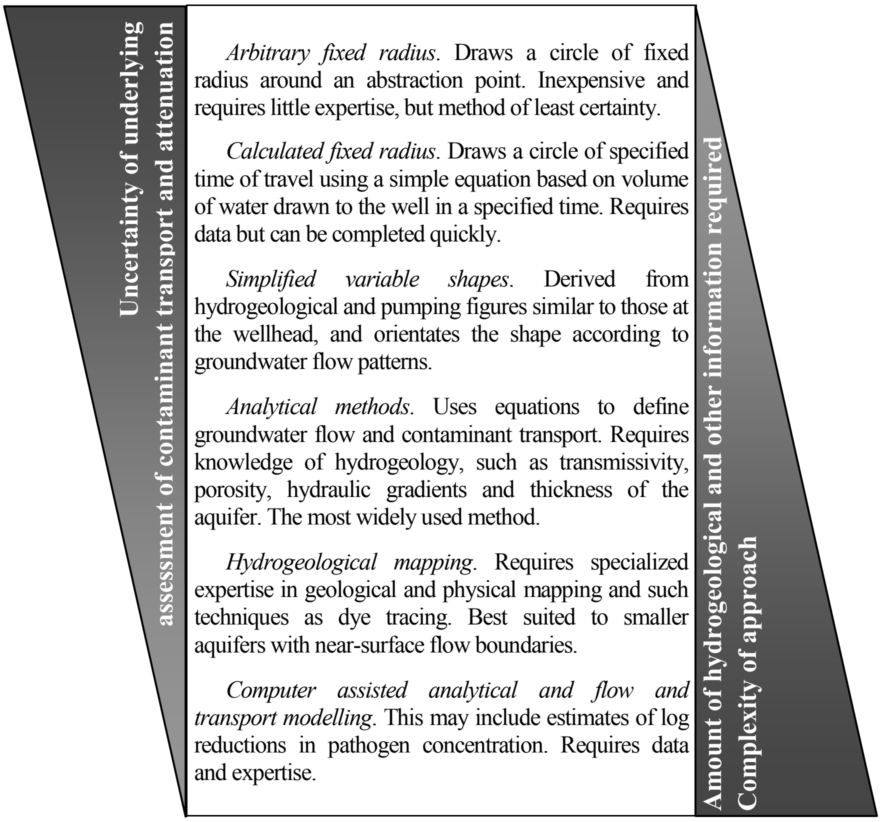

Figure 17.1. Approaches to delineating groundwater protection zones

In order to address some of the fundamental weaknesses in fixed distance approaches, more sophisticated protection zones can be defined based primarily on travel time of water through the saturated zone. For this purpose tracers are often used to acquire information about flow velocities and directions, and an overview of available tracer methods is given in Box 17.1.

Travel time approaches are more realistic in that they attempt to incorporate more empirical evidence, usually related to expected die-off of microbes or dilution of chemicals in defining the land area to be protected. Commonly time criteria are established that provide confidence that the concentration of contaminants will have been reduced to an acceptable level. Although such approaches are better able to reflect local conditions, there remain considerable uncertainties in the degree of protection afforded. In particular these approaches may not be the most cost-effective as they fail to take into account removal of contaminants through attenuation.

Box 17.1. Tracers used in defining groundwater protection zones

A key element in defining groundwater protection zones when using quantitative approaches is to identify tools that allow identification of basic hydrogeological parameters, such as flow rates and patterns, and to predict how pollutants will move through the subsurface. The latter is of particular importance as a means of quantifying the impact of attenuation and dilution.

The use of tracer tests is therefore highly recommended to acquire information about flow velocities and directions, hydraulic connections and hydrodynamic dispersion. Tracer substances can be divided in to two main groups: natural and artificial tracers. Natural tracers are already present in the study area and do not have to be added artificially to the system whereas artificial tracers have to be injected. The most common natural tracers are environmental isotopes and chemicals, organisms and physical effects such as temperature. Artificial tracers are dyes (fluorescent and non-fluorescent), salts, radioactive tracers, activable isotope tracers and particles (spores, bacteria, phages, microparticles, etc.). Table 17.1 provides a summary of selected tracers that are commonly used.

Table 17.1. Tracers commonly used in groundwater

Tracer	Examples	Advantage	Disadvantage	Comment
Natural environmental isotopes (stable/unstable)	^{2}H, ^{18}O, ^{3}H, ^{3}He, ^{4}He, ^{39}Ar, ^{85}Kr, ^{36}Cl, ^{13}C, ^{14}C, ^{34}S, ^{15}N, ^{234}U	No artificial input needed Huge spatial and temporal interpretation possible	Expensive measuring techniques due to low concentrations Complicated interpretation	Omnipresent substances (no artificial input required) Useful for calculation of mixing proportions, ages and travel times
Radioactive tracers	^{3}H, ^{51}Cr, ^{60}Co, ^{82}Br, ^{131}J, ^{24}Na	Low chemical impact on the environment Disappearance due to radioactive decay Easy and economic detection	Possible radiation during artificial input of the tracer More complicated evaluation	Have been applied as artificial tracers both in surface and groundwater with satisfying results; especially useful for sewage water with high amounts of suspended particles
Fluorescent dyes	Uranine	Economic Non-toxic Very low sorptivity High solubility in water	Sensitive to light and oxidizing substances Strong pH-dependence Difficult evaluation if Uranine is already in the hydrologic system	Very good tracer analysing ground-water-flow and flow-velocities Uranine should be restricted to groundwater in reasonable low concentrations

Tracer	Examples	Advantage	Disadvantage	Comment
Fluorescent dyes (continued)	Rhodamine B	Low sensitivity to light and pH High solubility in water	Carcinogenic High sorpitivity	Good tracer for short term tests and surface water with low contents of suspended organic and mineral particles
	Amidrhodamin G	Low sensitivity to light and pH Low sorpitivity High solubility in water Easy to measure parallel to Uranine		Good tracer for ground- and surface-water
Bacteria	*E. coli*, faecal streptococci, sorbitol fermenting bifido-bacteria	Transport behaviour models pathogenic bacteria movement	Limited persis-tence of sensitive indicator bacteria May have environmental rather than faecal source	Would not usually be injected directly as a tracer but monitored in relation to known hazard sites to determine impact
Bacteriophages	F-specific RNA bacteriophages, coliphages	Transport behaviour similar to viruses can be used as either index organism or process indicator	Isoelectric point and sorption dependent upon pH and need to ensure	Appropriate especially for investigating transport behaviour of viruses in order to define groundwater detection zones
Spores	*Clostridium perfringens*	Long survival times which can mimic more robust pathogens	Potential for interference by natural populations	Spores are often dyed or prepared to facilitate its transport behaviour and detection

The most sophisticated approaches to groundwater protection zone definition are based on calculated log-reductions in microbial concentrations or reductions in chemical concentrations that can be achieved through attenuation and dilution as contaminants move through the soil, unsaturated and saturated zones. These approaches require much greater knowledge of local conditions and the expected reductions that may be achieved through attenuation. They do, however, provide much more realistic estimates of the land area where control should be exerted on polluting activities, and thus may be components of quantitative risk assessments. These may involve assessment of the hazard arising from a particular activity, examination of the vulnerability of the underground water to pollution, and consideration of the possible consequences which would occur as a result of contamination.

Local conditions determine the choice of method as this depends upon the amount of expertise and data available. Technical considerations should include ease of applicability, extent of use, simplicity of data, suitability to the area’s hydrogeological character and accuracy required for decision-making purposes. The choice should also be related to relevance to the protection goal, and therefore may also include approaches that employ prioritization schemes for land use. Within each of the approaches adopted, it is important to also bear in mind the importance of other factors such as other sanitation provisions, economic impact and social norms.

The following sections briefly discuss approaches to defining and characterizing protection zones that have been adopted in different countries. Depending on the level of technical expertise and objectives of the groundwater protection, they are based chiefly on distance or travel time approaches (Section 17.3), or include more hydrogeological information to assess vulnerability (Section 17.4). A recent development is to assess contaminant loading and attenuation in order to use a risk assessment for protection zone delineation (Section 17.5). A supplementary criterion used in some countries is to include an assessment of current and future land use priorities in developing groundwater protection schemes (Section 17.6).

17.3 FIXED RADIUS AND TRAVEL TIME APPROACHES

The simplest form of zoning employs fixed-distance methods where activities are excluded within a uniformly applied specified distance around abstraction points. These methods use expert judgement and experience and have been widely applied. There is limited direct scientific evidence to underpin most fixed-distance approaches, as they do not take into account local hydrogeological conditions and aquifer vulnerability or the interaction between adjacent wells and the impact that this may have on local flow conditions. This reduces the confidence in the degree of protection that is provided. These approaches are often used when there is limited information on the hydrogeology of an area and are a practical means of ensuring a measure of immediate protection.

Fixed radius approaches are used in a number of countries for defining a protection zone around the immediate vicinity of the wellhead, chiefly designed to protect the wells from pollution by short cuts. For example, in Germany this zone is set at a minimum of 10 m for wells, 20 m for springs and 30 m for wells in karst aquifers. The Swiss, Danish and Austrian protection schemes also use an innermost zone of 10 m radius. In Australia the wellhead protection zone is a concentric area comprising the operational compound surrounding for the well and is often, but not always, defined as a 50 m radius within which the most stringent controls on land use and materials apply.

Distance approaches to define protection zones targeting effective attenuation of pathogens and/or substances to acceptable levels, often underpinned by travel time concepts, are also used. This may follow the calculated fixed radius or variable shape approach (see Figure 17.1). In practice travel times are not always determined for each specific setting, and both approaches may be used together, as is the case in Ireland and Denmark (see below).

They may also be supplemented by analytical methods and hydrological modelling, if sufficient scientific expertise and data is available. The delineation of protection zones can then be based on such issues as the recorded or modelled movement of pollutants through the groundwater area. In such cases, zones may not be simple concentric circles around abstraction points, but their boundaries follow the calculated time of travel of chosen parameters. This may be important in heavily developed areas where the imposition of restrictions within a defined area may have economic repercussions.

Examples from a number of countries are summarized in Table 17.2. These examples highlight how fixed distance and travel time approaches are used in practice in different countries, and selected approaches among these are discussed in the following. In some countries, however, fixed radius and travel time approaches are supplemented by more sophisticated methods as discussed in the following sub-sections.

Table 17.2. Comparative table of examples of protection zone dimensions

Country	Wellhead protection zone or inner zone	Middle zone	Outer zone
		Travel time and/or radius of zone	
Australia	50 m	10 years	Whole catchment
Austria	<10 m	60 days	Whole catchment
Denmark	10 m	60 days or 300 m	10-20 years
Germany	10-30 m	50 days	Whole catchment
Ghana	10-20 m	50 days	Whole catchment
Indonesia	10-15 m	50 days	Whole catchment
Ireland	100 days or 300 m	-	Whole catchment or 1000 m
Oman	365 days	10 years	Whole catchment
Switzerland	10 m	Individually defined	Double size of middle zone
United Kingdom	50 days and 50 m minimum	400 days	Whole catchment

Ireland

In Ireland, individual public water supply sources are identified and protection zones established around them – termed Source Protection Areas (SPA). Two SPAs are delineated – an inner protection area and an outer protection area (DoELG, 1999). Both areas may be identified either on the basis of a simple zoning using an arbitrary fixed radius where scientific and geological data is in short supply, or using hydrogeological methods based on local data or modelling.

Inner protection areas are intended to protect the source from the effects of an activity that could have an immediate effect on water quality, and is defined as a 100-day time of travel from any point below the water table. 100 days is chosen by Ireland as a conservative limit to allow for the heterogeneous nature of Irish aquifers and to allow for the attenuation and die-off of bacteria and viruses which may live beyond 50 days. In some karstic areas it is not possible to identify 100-day boundaries, in which case the whole aquifer becomes a SPA. If the arbitrary fixed radius method is used, 300 m is taken as an equivalent distance. The outer protection areas covers the zone of the aquifer, the recharge of which supports the long-term abstraction of the individual source (or the complete catchment if this is the contributing area), or, using the arbitrary fixed radius method, 1000 m.

In this example, although travel time is used as the underlying concept for defining the protection zone, simple practical measures based on a broad knowledge of the groundwater system are used to define protection zones. Generally, such approaches may have particular value for small supplies where gaining access to hydrogeological expertise may be difficult or expensive.

Ghana

In crystalline rock terrains such as that found in Ghana, the protection of boreholes cannot be simply achieved by establishing protection zones. This is because heterogeneous materials developed in the weathered zone and in fractures in the bedrock provide viable flow paths for contaminants from indiscriminately located latrines, waste dumps and other pollution sources at far away places (Bannerman, 2000). The high groundwater velocities would result in groundwater protection areas covering the major parts of communities' aquifers and hence may make them impractical to achieve.

In Ghana, a pragmatic time-of-travel approach has been adopted with which to define protection area boundaries. Three protective zones are designated. Zone I covers an area of radius 10-20 m around a production well and is designed to protect it against short-circuit contamination at the well site. Zone II is situated around Zone I, and comprises the zone between the well field and a line from which the groundwater will flow at least 50 days until it reaches the production well. The choice of this travel time for Ghana was developed from experience elsewhere though it may not be applicable under all conditions. Zone III is a buffer zone between the recharge area and Zone II. If the water is produced from a spring, the zone should not be less than 20 m on the upstream (uphill side) of the water source.

United Kingdom

In the United Kingdom decisions on protection zones are taken on the basis of assessing the likely impact of a pollutant and the degree to which attenuation occurs in the geological strata influencing the source. According to the national groundwater protection policy (NRA, 1992), three distinct protection zones are recognized in the vicinity of abstraction points:

The Inner Source Protection Zone (Zone I) is located immediately adjacent to the groundwater source, and is designed to protect against the effects of activities which would have an immediate outcome on the source, in particular in relation to the release of pathogens into groundwater. It is defined as the area within which water would take 50 days to reach the abstraction point from any point below the water table, subject to a minimum of 50 m radius from the source.

The Outer Source Protection Zone (Zone II) is an area defined by a 400 day travel time to the source. It is based upon the time needed for the attenuation of slowly degrading pollutants. In England and Wales this is further modified for aquifers of high water storage capacity, such as sandstones, to allow for Zone II to cover either the area corresponding to 400 days, or the whole of the recharge area, calculated on the basis of 25 per cent of the long term abstraction rate for the source.

There is a further zone (Zone III) which covers the whole of the catchment area of the source, based on the area needed to maintain abstraction assuming that all water will eventually reach the abstraction point. In some cases, where the aquifer is confined, it is possible that the protection area is remote from the site of the source.

Denmark

Denmark has used a protection system which takes account of existing abstraction wells and utilizes two zones. The first is a 10 m fixed radius zone immediately surrounding the abstraction point to provide for technical and hygienic protection. The second zone of 60 days travel time or 300 m radius acts as an outer protection area to take account of contaminants which degrade more slowly.

Problems in dealing with pesticide contamination have also led to the consideration of a 10-20 year zone in which pesticides would be controlled. Evidence of continuing problems with groundwater quality, particularly in respect of pesticide contamination and rising nitrate levels, led the Danish Government to adopt a three zone system in 1998 to prioritize the expenditure of money and effort in controlling, particularly, point sources of pollution (Stockmarr, 1998) (discussed below in Section 17.6).

Germany

In Germany guidelines on the definition of zones are available through a code of practice (DVGW, 1995). It defines three zones. The Well Field Protection Zone (Zone I) is designed to protect individual wells and their immediate environment against any contamination and interference and has fixed dimensions of 10 m. A Narrow Protection Zone (Zone II) aims to provide protection against contamination by pathogenic bacteria and viruses and is based on a 50 day travel time. Due to the area of land required to meet the 50-day criterion, fixing a boundary is often not possible in karst terrains, mainly for economic reasons (for example where existing development would have to be removed). In such cases, Zone II may be smaller, but should in any case comprise all areas from which an increased risk to the karst aquifer may emanate.

A Wide Protection Zone (Zone III) serves to protect wells against long-range impairments, notably against contamination by non-degradable or less readily degradable chemical or radioactive substances, and usually covers the entire subsurface catchment area. If the catchment area is very large, with a boundary more than 2 km from the well, it may be sub-divided into Zone III A and Zone III B, with different levels of land use restrictions.

The Code of Practice also addresses particular cases such as the definition of protection zone boundaries for very large catchment areas or when several wells are located in the same catchment area. In general, the size of the area to be placed under protection is dependent upon the abstraction and recharge rates in the catchment area, the higher the abstraction rate the larger the protection zones to be defined. The Code of Practice also includes guidance for the definition of protection zone boundaries in the case of water production from several (geo)hydraulic systems and in the case of artificial recharge.

Australia

The Australian wellhead protection plan is a system of groundwater protection which involves four components. These comprise a set of actions to ensure that the well is properly designed and constructed (known as 'well integrity assurance') the setting up of wellhead protection zones, an appropriate monitoring system, and contamination or land use control (ANWQMS, 1995).

The wellhead protection zones are based on the definition of concentric protection zones around the wellhead. Zone I encompasses the operational compound surrounding the well, and is often, but not always, defined as a 50 m radius area within which the most stringent controls on land use and materials apply. Zone II is arbitrarily defined as the maximum distance a contaminant particle would have travelled if it took 10 years to reach the well. Zone III corresponds to the regional protection area where greater than 10 years travel time is available. This is usually the catchment area of the contributing aquifer.

Oman

In some countries, where water is in short supply and resources are very limited, protection zones are used primarily to ensure that there is adequate control over abstraction rates. This applies particularly to arid countries

For example in Oman, because of problems of water derogation, the water resources Council in 1983 decided that no wells should be constructed within 3.5 km of a motherwell of a water supply system (*falaj*). The choice of size of the protection zone was a pragmatic solution rather than being based on hydrogeological principles. Since that date the protection of groundwater has been accomplished by the adoption of National Water Development Areas – water protection zones designated for the general protection from contamination, over-extraction, intrusion by seawater and adverse development.

The schemes used a colour-coded zoning system to identify specific limitations on future developments and progressively on existing activities. Such zones were a response to already perceived potential problems and were useful in providing guidance on future developments within the water protection zones. However they had limited success in dealing with existing development due to the problems of applying retrospective controls. In response a new scheme using technically derived zones based on time-of-travel periods has been developed to accommodate this (Government of Oman, 1991).

The establishment of major government wellfields in urban areas to meet public water supply needs was followed by the recognition that these needed careful protection both as a water resource and from pollution (Government of Oman, 1991). As a further refinement of the earlier water development area zoning system described above, a revised water protection zone concept utilizing three distinct zones with relevant regulation of activities within them has been adopted. The three zones use 365 days as the time of travel to define the boundary of an innermost protection zone surrounding an abstraction point such as a well. A second tier protection area which uses a 10 year time of travel to define the boundary is established as a middle protection zone, whilst the extent of the third and outermost protection zone is delineated by the catchment boundary.

Indonesia

An integrated approach to ensure proper drinking-water quality in urban centres of Indonesia has been developed by the Indonesian-German governmental cooperation on drinking-water quality surveillance. This concept includes protection zones to protect and maintain water resources in their initial function and allotment by a natural and preventive approach. The zones are based on fixed distances for Zone I and on travel time for Zone II, using hydrogeological mapping and a flow path model where protection zones of different categories are defined. The following zones are applied:

- Zone I is defined as the area surrounding the spring/well within a radius of 10-15 m, which is fenced and where any activity that has interaction with the aquifer is prohibited.
- Zone II is the boundary that is defined by 50 days travel time, to provide protection against bacteriological contamination. In order to determine the boundaries, a hydrogeological survey is conducted for each spring and well. Besides the restrictions mentioned under Category III, all possible activities causing bacteriological contamination are prohibited.
- Zone III includes the whole catchment area based on topographical boundaries where the application of water hazardous pesticides, the infiltration of liquid waste, human settlements with unorganized discharge of the waste water within the catchment area and waste disposal are restricted. Clustering of several springs/wells in one catchment area is possible.

17.4 APPROACHES USING VULNERABILITY ASSESSMENTS

A number of countries (e.g. the United Kingdom, Australia and Ireland) have introduced vulnerability assessment of groundwaters into their protection policies (for a discussion of the concept of vulnerability see Chapter 8). Such vulnerability assessments correspond to the concept of system assessment in the context of developing a Water Safety Plan. They can refine protection categories defined by fixed distance and/or travel time approaches and allow a differentiated management response within a protection area. Such systems are also useful outside of drinking-water protection zones for long term planning of the protection of groundwater resources. Further, they provide guidance to organizations concerned with major works activities that could cause problems of groundwater contamination, such as the siting of new industrial or urban developments.

The example of Ireland highlights how vulnerability assessments have been included in protection plans. The Irish Environmental Protection Agency has proposed a protection zone identification scheme based upon the division of the entire land surface according to the vulnerability of the underlying groundwater to contamination (DoELG, 1999). In this system vulnerability depends upon the time of travel of contaminants through the strata, the relative quantity of contaminants which can reach the groundwater and the attenuation capacity of the local geology. These factors are dependant upon the subsoil characteristics, whether the contamination source is point or diffuse source and the thickness of the unsaturated zone. Assessing these factors results in classification of the vulnerability of a given area as extreme, high, moderate or low. Such ratings are based on judgement, experience and available scientific information. The resultant map shows the vulnerability of groundwater to pollution from contaminants released at 1-2 m below the surface. Where deeper discharges are made, site-specific local conditions would have to be taken into account. The characteristics of the contaminants are not considered. This vulnerability classification is not only used for drinking-water resources, but also applied to the whole land surface of the country.

For drinking-water resources, the resultant map is then overlain with the simple map of the inner and outer Source Protection Areas derived as discussed above in Section

17.3 (Figure 17.2). This results in a map showing the vulnerability of both the inner and the outer SPA. While the inner SPA will usually be too small to contain more than one or two vulnerability categories, the outer zone might encompass all four. This map is the basis for defining the level of protection to be implemented for each area (Section 17.7)

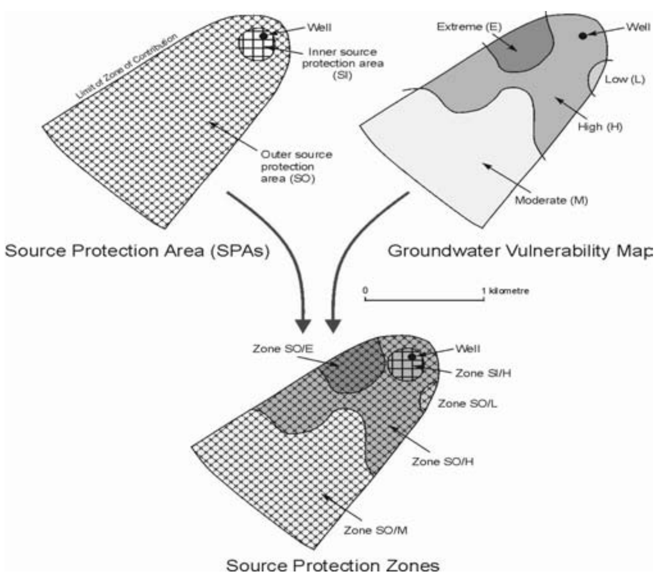

Figure 17.2. Delineation of source protection zones around a public supply well from the integration of the SPA map and the vulnerability map (DoELG, 1999)

17.5 A RISK ASSESSMENT APPROACH FOR DELINEATING PROTECTION ZONES

From 2001, a new policy for production of safe drinking-water in The Netherlands has been incorporated into legislation. This approach sets the health-based target of a maximum acceptable infection risk of one per 10^4 persons per year associated with drinking-water consumption. It then uses dose-response relationships for pathogens to determine maximum allowable pathogen concentrations in drinking-water (Regli *et al.*, 1991). In the case of viruses, it is based on the dose response relationship of rotavirus and poliovirus 3, as a worst-case. The maximum allowable concentration is 1.8×10^{-7} viruses per litre. Together with data on the occurrence of virus concentrations in surface water this implies that they need to be reduced by a factor of 5-8 $\log_{10}$ in order to produce drinking-water in which maximum allowable concentrations are not exceeded. Drinking-water companies that use surface water as a source (approximately one third of the total drinking-water production in The Netherlands) are therefore obliged to conduct a risk analysis to demonstrate adequate drinking-water treatment. Vulnerable groundwater systems may also be subject to this risk assessment. This raises the question whether current protection zones of 60 days of travel time are sufficient and actually what travel times and travel distances are needed to comply to the risk level of 10^{-4} per person per year.

Therefore, and as a first step in a vulnerability analysis of Dutch groundwater well systems to virus contamination, a hypothetical case was simulated to calculate the travel distance and time that are required for sufficient protection against virus contamination (Schijven and Hassanizadeh, 2002a; 2002b). The conditions assumed are given in Table 17.3 below. In this simulation a sewage pipe was continuously leaking virus. The virus was diluted and transported with the groundwater that was abstracted by a single well (radial flow). This hypothetical case was based on data from a field study on deep well injection (Schijven and Hassanizadeh, 2000) and a number of conservative assumptions.

Table 17.3. Conditions applied in the Dutch study for calculating required travel times and distances to adequately protect groundwater wells in unconfined shallow sandy aquifers against virus contamination (Schijven and Hassanizadeh, 2002a; 2002b)

Condition assumed for the model calculation	**Evaluation of assumptions used**
Shallow sandy aquifer High permeability Groundwater table 0.5-1 m below surface Depth of aquifer: 20-30 m	Sources of contamination do occur directly in the aquifer
Unconfined	Absence of protecting confining layers is typical
	Local differences occur in the thickness of confining layers due to irregularities and effects of erosion are regarded as a considerable source of uncertainty for protection
Temperature: 10 °C	Typical value for Dutch aquifers from 1 m below surface at groundwater table
pH 7-8	Typical values
Bacteriophage MS2 as a model virus	Represents poorly adsorbing viruses
Anoxic conditions	Do occur and result in the absence of favourable sites for attachment like ferric oxyhydroxides
	Low inactivation rate of MS2 (0.024 day^{-1}) has been demonstrated
Saturated conditions	Result in less attachment or inactivation compared to unsaturated conditions
Point source of contamination at water table	Worst case assumption, as horizontal transport is shortest pathway
Continuously leaking sewage pipe ($1\ m^3/h$)	Realistic scenario for a steady state where low leakage rate remains unnoticed
Approximately 200 enteroviruses per litre in raw wastewater	Average value for concentrations in raw wastewater in The Netherlands
Maximum allowable virus concentration at abstraction well of 2×10^{-7} viruses per litre	Based on drinking-water consumption, virus infectivity and probability of infection of 10^{-4} per person per year
Required reduction of virus concentration 9 $\log_{10}$	Based on measured source concentration and maximum allowable concentration at the well

Under the anoxic conditions of the deep well injection study minimal removal of virus was observed, i.e. there was little attachment of virus to the grains of sand and little inactivation of virus. The same conditions were assumed to apply as well to a selection of six unconfined sandy aquifers. The absence of confining layers together with the shallowness of the aquifers and unfavourable conditions for attachment make it a reasonable assumption qualifying these groundwater well systems as relatively vulnerable.

These and other conditions applied to calculating the required travel times and distance are listed in Table 17.3. Concentrations of enteroviruses in raw domestic wastewater from the leaking pipe need to be reduced by 9 $\log_{10}$ at the point of groundwater abstraction. A steady state solution of a transport model incorporating attachment and inactivation was applied to calculate travel times and distances to achieve this.

Virus concentration was found to be reduced by 3.1-4.0 $\log_{10}$ at the abstraction well due to mixing with groundwater from all directions (radial flow). To account for an additional 5.0-5.9 $\log_{10}$ removal of virus by attachment and inactivation, residence times of about 8 to 15 times longer than the current guideline of 60 days appeared to be needed, depending on abstraction rates, aquifer thickness and sand grain size. At a higher transport velocity, removal with distance is less, but this is partly compensated by a higher dilution factor.

Although this hypothetical case was partly built on conservative assumptions, it strongly indicates that a 60-day protection zone is insufficient by far to protect against virus contamination from a nearby leaking sewage pipe. The situation may even be worse. Concentrations of noroviruses in raw wastewater (Lodder *et al.*, 1999) were found to be 10^4 to 10^6 RNA-containing particles per litre as determined by PCR, which is 10^2 to 10^4 times higher than that of enteroviruses as determined by tissue culture. However, it is uncertain what part of the RNA containing particles is actually infectious.

Compared to the removal capabilities of sandy aquifers, removal of viruses in karst, fractured bedrock and gravel aquifers may be lower. Such aquifers are identified as sensitive to faecal contamination by the US EPA's proposed Ground Water Rule (US EPA, 2000). These aquifers have in common that more permeable pathways exist that allow very high flow rates of viruses (Rossi *et al.*, 1994; Paul *et al.*, 1995; 1997). In such pathways, attachment will be very low. Due to the high transport rate (short travel times), inactivation will also be minimal. In gravel, removal of slug-injected bacteriophages T7 and H40/1 was only 2 $\log_{10}$ over a travel distance of 50 m (Rossi, 1994; Rossi *et al.*, 1994). This is about the same removal rate as for MS2 in a sandy anoxic aquifer. In fact, T7 and H40/1 were probably removed more effectively than MS2, considering the coarseness of gravel. Even considerable removal may be found in fractured rock, e.g. about 6-$\log_{10}$ removal of MS2 over a distance of 20 m in limestone (Paul *et al.*, 1997) or 1-$\log_{10}$ removal of MS2 and PRD1 over a distance of 0.5 m in a clay-rich till (Hinsby *et al.*, 1996). Nevertheless, it is obvious that preferred pathways, like fractures and breaches, will contribute greatly to the uncertainty in assessing the removal capabilities of a certain aquifer.

As these examples highlight, using a risk assessment approach for delineating protection zones requires an understanding of the elimination capacity of the unsaturated zone and the pathogen levels expected to reach the well. Often this information will not be available specifically for a given setting, and estimates can be derived from assessing pollution potential as discussed in Chapter 14.

17.6 PRIORITIZING SCHEMES FOR GROUNDWATER PROTECTION

In situations where land use pressures are high – e.g. for increasing agricultural production or where land for building is at a premium – and such land is also liable to overly the available water resource, systems of prioritization are necessary to control development of the land in such a way that the availability and quality of water supplies is not jeopardized. The benefit of prioritization approaches is that they promote cost-effective application of protection zones to take into account the need to balance economic development and resource protection. Thus they may be used as a further criterion in defining management responses, supplementing hydrogeological criteria such as travel times and vulnerability assessments. This is currently practiced in some countries, and examples are given below.

Western Australia

In Western Australia groundwater resources used for public supply are protected from pollution by being proclaimed Underground Water Pollution Control Areas and using by-laws to control activities which could potentially pollute such resources. Instead of using simply an assessment of vulnerability to pollution, the Western Australian system recognizes that water source objectives vary dependent upon the strategic importance of the source, its vulnerability and other competing land uses. The result is a three tiered priority-based system with management objectives for each priority area. Besides vulnerability, these include such issues as designated beneficial uses (for example drinking, irrigation, industrial, recreation or ecosystem protection), water quality, social, economic and ecosystem value, and current and planned land use. This assessment enables the areas on the vulnerability map to be classified in terms of the requirements for protection, and allow action levels to be set to give the required protection.

The city of Perth overlies a large fresh groundwater resource (see also Chapter 14.6 for further details). Groundwater forms an important component of the city's water supply, providing 70 per cent of water used, and also maintaining ecosystems around environmentally significant lakes and wetlands. The groundwater occurs as an unconfined aquifer throughout the region, and in several confined aquifers. The shallow groundwater in urban areas is highly susceptible to contamination owing to the sandy soil, and in some areas this has restricted groundwater use, and has had an adverse impact on wetlands. The growth of the urban area has overtaken well fields previously located in areas of rural land use, and has compromised water quality. Land use in these areas is now controlled by Priority SPAs. There are three types of protection areas:

- *Priority 1* (P1) SPAs are defined to ensure that there is no degradation of water quality used for public supply. P1 areas are declared over land where the provision of the highest quality public drinking-water is the prime beneficial land use. P1 areas include government owned land where there is no development, or use is limited to forestry or sylviculture.

- In *Priority 2* (P2) SPAs previously existing land uses are regulated to ensure that there is no increased risk of pollution to groundwater quality. P2 areas are declared over land where low intensity development (such as rural) already exists. Provision of public water supply is a high priority in these areas, but there may be some degradation of water quality.
- *Priority 3* (P3) is declared over land where water supply needs co-exist with other land uses such as residential, commercial and light industrial developments. Protection of groundwater quality in P3 areas is achieved through management guidelines rather than restrictions on land use.

In Western Australia a corridor plan is in operation. In this plan, urban development takes place in northwest, southwest, southeast and eastern corridors ensuring that the central part of the coastal plain, where the groundwater recharge areas are located, will be essentially undeveloped, thus providing a further layer of long term protection. Future expansion of the public water supply will take place by extending the well fields north and south over the groundwater mounds.

Tunisia

In a further development of the protection zone concept for groundwater resource management in Tunisia, in essence formalizing the Western Australian approach, economic and social value factors have been introduced into the assessment of the need to protect groundwaters (Findikakis *et al*., 1998). This is a useful concept where supplies are very scarce, and where alternatives are limited, for example in arid countries. The system uses three groups of criteria which take into account the physical nature of the resource, its vulnerability to pollution or depletion by over-abstraction and the socioeconomic value of the aquifer. This latter is an important factor where aquifers are in isolated regions and where they form the main water supply source. The socioeconomic value is based on an economic indicator that identifies the relative economic importance of the supply taking into account the level of economic production dependent upon the source, and the number of people dependent upon it.

Denmark

Since 1998, Denmark defines three zones in relation to value for use, the most critical of which comprise areas of special interest for drinking-water (Stockmarr, 1998). These are defined as areas sufficiently large to supply the population in the future, taking account of other water uses. Such zones will be established in each administrative county and will eventually cover about 15 to 30 per cent of the total land area. Areas of minor interest for drinking-water are areas where groundwater is already heavily contaminated, and which represent areas of land within which such activities as landfill operation should be concentrated. These areas are generally expected to be a minor zone along the coastline where abstraction is not generally practised. The third zone will comprise most of the remaining land areas and represent land which may become important water supply areas over the next 20 to 30 years, known as areas of interest for drinking-water.

The areas are identified by reference to the classification of groundwater resources taking account of precipitation and evaporation, median river water flows, run-off, groundwater potential and catchment areas, relevant geological features, land use, and so forth, and maps will show the groundwater resource divided into the three categories.

The resultant areas of special interest for water resources are then subject to limitations on the use of land use for activities such as the location of industry or urban development.

United States of America
A draft prioritization scheme was developed by the US EPA (1986). Although this was never finalized and implemented, the approach may be of interest to readers of this monograph. The scheme combines vulnerability, quality and the resource's value to society. Three classes are identified as set out in Figure 17.3 below. Different levels of management of the overlying land are applicable to each class of groundwater under this scheme.

Classifying groundwaters under this system involves delineating a segment of the groundwater body to which the classification criteria applies. This is known as the Classification Review Area and comprises a two-mile radius from the boundaries of the activity that may affect the particular groundwater (such as the edge of a contaminated area or the proposed abstraction point). The review area is not necessarily a regulatory area at this stage.

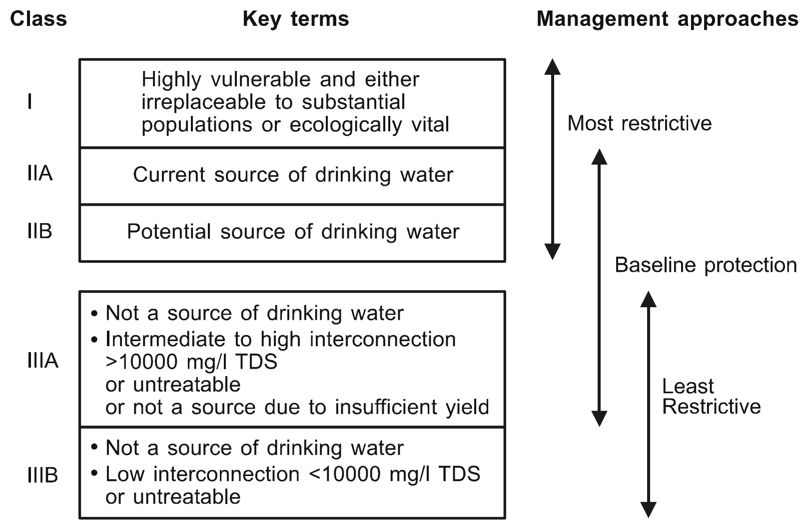

Figure 17.3. US EPA classification scheme (US EPA, 1986)

Where important sources of water are concerned, i.e. the Class I category of groundwaters, a ranking system (DRASTIC) is used to identify further the vulnerability in order to enable suitable protection procedures to be applied. The method yields a single numerical value, referred to as the DRASTIC index. The use of DRASTIC is commensurate with the idea that groundwater vulnerability should not vary according to the type of activity that is being evaluated. This system represents a common methodology which may be used on an interstate basis.

As an alternative means of assessing vulnerability, qualitative assessment may sometimes be an option, wherein the selection of vulnerability might be based on site setting, professional experience of the user, the availability of data, or previous experience. However, this option does not permit the use of referred tests and methods or other numerical criteria or decision steps.

Most of the States in the USA also have individually developed groundwater classification systems, as shown in Table 17.4.

Table 17.4. Groundwater classes based on usability and/or quality criteria used in some States of the USA (US EPA, 1985)

State	No. of classes	Criteria for classification
Connecticut	4	1. Suitable for drinking without treatment; 2. May be suitable for drinking without treatment; 3. May have to be treated; 4. May be suitable for waste disposal practices
Florida	4	1. Single source aquifers suitable for potable use; 2. Potable use TDS $<$10 000 mg/l; 3. Non-potable use from unconfined aquifers; 4. Non-potable use from confined aquifers
Guam	3	1. Drinking-water quality; 2. Saline; 3. Size criteria
Maryland	3	1. TDS $<$500 mg/l; 2. TDS 500-6000 mg/l; 3. TDS $>$6000 mg/l
Massachusetts	3	1. Drinking-water quality; 2. Saline; 3. Below drinking-water quality
Montana	4	1. Suitable for drinking-water; 2. Marginally suitable for drinking-water; 3. Suitable for industrial or commercial; 4. May be suitable for some uses
New Mexico	2	1. TDS $<$10 000 mg/l; 2. TDS $>$10 000 mg/l
New York	3	1. Potable use; 2. Saline water 250-1000 mg Cl/l; 3. Saline water $>$1000 mg Cl/l
North Carolina	5	1. Drinking-water; 2. Brackish water $>$20 feet below surface; 3. Fresh water $<$20 feet below surface; 4. Brackish water $<$20 feet below surface; 5. Not suitable for drinking
Vermont	2	1. Drinking-water; 2. All other groundwaters
Wyoming	7	1. Domestic; 2. Agricultural; 3. Livestock; 4. Aquatic life; 5. Industry; 6. Hydrocarbon and mineral deposits; 7. Unsuitable for any use

17.7 MANAGING LAND USE AND HUMAN ACTIVITIES IN PROTECTION ZONES

The beneficial use of protection zones relies upon the ability to restrict polluting activities in them. Commonly this is achieved through the activation of legislation which is available under the land use planning or pollution control regimes of the country. The designation of the zone triggers specific requirements, which are met by enacting relevant restrictions or introducing permitting systems. Often it is not necessary to introduce new legislation. The designation of the protection zone may require that the body which administers planning or pollution control laws takes action to ensure that they are applied rigorously and deal with the particular concerns brought about by recognition of the special characteristics of the protected area. However, this may not be trivial. Stricter application of existing legal requirements may require changes of habitually established land uses (e.g. horticulture with intensive pesticide application), and this may have substantial socioeconomic implications. Therefore, new designation of protection zones may require programmes that include compensation payments or other forms of financial support of current land users affected by the change.

Furthermore, the implementation of measures to control activities in a drinking-water catchment may be facilitated by integrating them into a Water Safety Plan (WSP), as this helps communicate their importance for achieving the quality targets. Further, developing catchment control measures in a WSP-team together with stakeholders involved in activities in the catchment improves their understanding of these issues and can thus improve their sense of ownership and responsibility for protecting the catchment.

In addition to identifying and designating the protection zones or vulnerable areas, it is important to provide guidance on activities which are either acceptable, unacceptable or need to be controlled in the various zones. Restrictions on land-use and other human activities may become control measures in a WSP, and compliance can be monitored through visual inspections in the drinking-water catchment. This is particularly feasible in some countries where such lists are extensive and very specific. In others general guidance is issued.

In the following, examples will be discussed that show different concepts of managing authorization or restrictions of land use and human activities in protection zones.

Western Australia

In the Western Australian system where activities are planned to take place within the P1, P2 and P3 priority zones (see Section 17.6), reference to specific guidance on compatible, incompatible and conditional activities must be given. Activities which are compatible may be undertaken without restriction. Those activities identified as being incompatible with the objectives of the priority classification can only be carried out after a formal EIA has been carried out. Conditional activities require appropriate site management practices and referral to the Water and Rivers Commission (which is responsible for water quality) for assessment on a case specific basis.

As examples, Table 17.5 lists some of the commercial activities which need to be assessed if they are to be permitted in groundwater protection areas in Western Australia. Similar tables exist for industrial activities, agriculture, urban development, education and research, mining and mineral processing, animal and plant processing, waste treatment and a number of other categories.

Table 17.5. Examples of commercial developments subject to control in water protection zones in Western Australia (based on WRc, 1996)

Land use	Priority 1	Priority 2	Priority 3
Aircraft servicing	Incompatible	Incompatible	Conditional
Airports or landing grounds	Incompatible	Incompatible	Conditional
Amusement centres	Incompatible	Incompatible	Compatible
Automotive businesses	Incompatible	Incompatible	Conditional
Boat servicing	Incompatible	Incompatible	Conditional
Catteries	Incompatible	Compatible	Compatible
Caravan and trailer hire	Incompatible	Incompatible	Conditional
Chemical manufacture/formulation	Incompatible	Incompatible	Conditional
Consulting rooms	Incompatible	Incompatible	Compatible
Concrete batching and cement products	Incompatible	Incompatible	Conditional
Cottage Industries	Conditional	Conditional	Compatible
Dog kennels	Incompatible	Conditional	Conditional
Drive-in/take-away food shops	Incompatible	Incompatible	Compatible
Drive–in theatres	Incompatible	Incompatible	Compatible
Dry cleaning premises	Incompatible	Incompatible	Conditional
Dye works	Incompatible	Incompatible	Conditional
Farm supply centres	Incompatible	Incompatible	Conditional
Fertilizer manufacture/bulk storage depots	Incompatible	Incompatible	Conditional
Fuel depots	Incompatible	Incompatible	Conditional
Garden centres	Incompatible	Incompatible	Compatible
Laboratories (analytical, photographic)	Incompatible	Incompatible	Conditional
Markets	Incompatible	Incompatible	Compatible
Mechanical servicing	Incompatible	Incompatible	Conditional
Metal production/finishing	Incompatible	Incompatible	Incompatible
Milk transfer depots	Incompatible	Incompatible	Conditional
Pesticide operator depots	Incompatible	Incompatible	Incompatible
Restaurants and taverns	Incompatible	Incompatible	Compatible
Service stations	Incompatible	Incompatible	Conditional
Shops and shopping centres	Incompatible	Incompatible	Compatible
Transport and municipal works depots	Incompatible	Incompatible	Conditional
Vehicle parking (commercial)	Incompatible	Incompatible	Compatible
Vehicle wrecking and machinery	Incompatible	Incompatible	Conditional
Veterinary clinics/hospitals	Incompatible	Incompatible	Conditional
Warehouses	Incompatible	Incompatible	Conditional

Germany

In Germany the Code of Practice for drinking-water protection areas includes, for the various zones, a listing of potential hazards and the resultant use prohibitions. Not all hazards listed in this catalogue will apply to the catchment area of a given well which is to be placed under protection and therefore local conditions are always considered in the vulnerability assessment. Table 17.6 provides a summary of controlled activities in the code of practice. These only constitute recommendations that need not necessarily be followed if local conditions so warrant.

Table 17.6. Examples of activities controlled in water protection zones in Germany (based on DVGW, 1995)

Zone type	Zone category	Controlled or prohibited activities
Wider protection zone	*Zone III B*	Industrial estates Pipeline systems for the conveyance of substances constituting a hazard to water Central sewage treatment plants, release of waste water to the ground Waste disposal facilities Agriculture (animal husbandry, application of fertilizers and pesticides) Air fields, Military facilities Sites for freight handling (freight railway stations, truckheads) Use of leachable substances constituting a hazard to water Mining
	Zone III A	*Hazards listed for Zone III B, plus:* Local sewerage systems Discharge of waste water into surface waters Transportation systems, unless waste water generated by these systems is piped out of Zone III A Petrol stations, motor racing Extraction of minerals and rock (near-surface resources) Penetration of strata overlying groundwater (e.g. civil engineering excavations), drilling operations Use of pesticides on road and railway areas
Outer zone	*Zone II*	*Hazards listed for Zone III A, plus:* Roads, railway lines and similar facilities for transportation Transportation of radioactive or other substances constituting a hazard to water Storage of fuel oil and diesel fuel, storage of fertilizers and pesticides Construction sites Livestock grazing Transportation of sewage or waste water Contaminated surface waters Release of storm water to the ground Swimming and camping facilities Shooting and blasting operations
Inner zone	*Zone I*	*Hazards listed for Zone II, plus:* Any type of traffic (whether vehicle or pedestrian) Use for agriculture or forestry Use of fertilizers and pesticides

United Kingdom

The situation in the United Kingdom is handled rather differently. Whilst the Environment Agency (EA) has its own direct powers under water pollution control legislation to authorize industrial activities which discharge to groundwater, it has no control over the general authorization or prohibition of other activities.

In order to give guidance to those with responsibility for such developments, a series of policy statements has been issued for the guidance of these organizations, primarily local councils which issue permissions within the context of land use planning legislation. The EA, acting as a statutory consultant at the planning consultation stage, would object to a number of activities in groundwater protection zones unless specific precautions were applied through the planning permission granted by the local authority. This gives a wide-ranging opportunity for the planning authority to insert specific protective measures into any permissions which it may grant. Because the policy statements are of a general nature, the EA is able to take account of local situations in the advice it gives to local authorities. Where other activities may be under consideration by governmental or similar responsible bodies (dealing with, for example, changes in farming practice, or pesticide formulation and use) the requirements for protective measures can be introduced at an early stage of the development. The restricted activities include polluting industries such as:

- waste management and landfill;
- activities which interfere with groundwater flow such as quarrying and gravel extraction;
- mining;
- construction of highways, railway cuttings and tunnels;
- borehole construction;
- field drainage that intercepts recharge water and any other activity that interconnects naturally separate aquifers;
- waste disposal to land;
- disturbance or redevelopment of contaminated land as a result of former industrial activities;
- the application of liquid effluents, sludges and slurries to land;
- the discharge of sewage effluent, industrial effluent, contaminated surface water into underground strata;
- other activities such as production, storage and use of chemicals, farm wastes, oil and petroleum.

Ireland

The Irish Groundwater Protection Scheme (DoELG, 1999) uses the vulnerability rating discussed in Section 17.4 as a basis for determining the level of protection (response) within the inner and outer zone. Four levels of response are defined for activities within a protection zone: acceptable (R1); acceptable in principle though subject to specified conditions (R2); not acceptable in principle though specified exceptions might be allowed (R3); and not acceptable (R4). Whereas activities within drinking-water protection zones will usually be classified as R4, an R3 rating is possible if vulnerability is low. R1 and R2 responses may be used outside of drinking-water protection zones, also depending on vulnerability.

A useful element of the Irish scheme is that it explicitly addresses uncertainty of classifications, depending on the quality of the hydrogeological and other information available. Regulatory bodies are invited to revise zone maps as information improves, and a bias towards ensuring protection may be addressed by a developer through providing new information which would enable the zoning to be altered and – if that proves adequate – the regulatory response correspondingly changed.

Indonesia

As part of the Indonesian groundwater protection approach, local regulations need to be developed and enacted which describe both protection zone boundaries and corresponding land use restrictions. The development of the local protection scheme requires an evaluation of contaminant sources within each zone as well as effective control measures for protecting the groundwater source. On the basis of a numeric scoring system the urgency of individual control or protection measures and related costs are ranked in order to prioritize individual activities. Based on this the head of district or governor issues a decree for each spring or well in which protection zone boundaries are marked and restrictions are defined in detail.

Implementation is part of the regional development plan. A multisectoral team of governmental and non-governmental experts is entrusted to plan and evaluate the progress of the establishment of the water protection zones. Community participation is a key issue in processing the protection zones. Financing comes from the local governments.

Currently the system is applied in three districts at Lombok Island and is under development in three other provinces. An example of the approach is given Table 17.7. The Indonesian Drinking Water Surveillance regulation stipulates the application of this system on a nationwide scale.

Table 17.7. Protection scheme for the spring-fed Narmada water supply (Lombok Island, Indonesia)

Protection zone	Identified contaminant sources	Generally restricted activities in protection zone	Control measures for the protection of the drinking-water source	Evaluation of control measures			Implementation priority
				Measure	*Cost*	*Total*	
Zone I: Fixed radius of 10-15 m	*Farm and rice fields*: microbial and chemical contamination from manure and chemical fertilizers and pesticides	All activities that directly impact on water quality, such as bathing and washing in ponds and streams	Repairing of the fence that protects the spring box	3	1	4	Priority I
	Fish ponds: microbial and chemical contamination due to short-circuits between ponds and groundwater	Any use of fertilizers and manures	Implementation of a training programme on best farming practices with regard to the use of fertilizers	3	3	6	Priority I
	Private drinking-water wells: direct ingress of microbial contamination due to unsanitary construction of wells or unsanitary practices	All activities that impact on water quality in ponds, i.e. solid and/or liquid waste disposal	Inspection and surveillance of farming practices	3	3	6	Priority I
	Solid waste disposal at the Sumberawan Temple: leaching of chemicals into groundwater	Any disposal of solid waste at the Sumberawan Temple site	Maintenance and surveillance of spring box	3	3	6	Priority I
			Provision of moveable solid waste bags at Sumberawan Temple	3	2	5	Priority I
Zone II: Boundaries: up-stream 315 m; downstream 40 m; side boundaries from 160-250 m	As in Zone 1 above	Use of manure and chemical fertilizers in excess application rates, i.e. in contradiction to best farming practices	Implementation of a training programme on best farming practices with regard to the usage of fertilizers and pesticides	2	3	5	Priority II
	Deforestation: devastation of the recharge area	Felling forest	Promotion of usage of environment friendly pesticides	2	2	4	Priority III
		Change of land use	Development of locally adapted best farming practices	1	3	4	Priority III
			Inspection and surveillance of farming practices	2	3	5	Priority II
			Afforestation programme	2	1	3	Priority IV

Control measure ranking: Very urgently required = 3; Urgent = 2; Less urgent = 1; Cost ranking: High cost = 1; medium cost = 2; low cost = 3

17.8 MONITORING AND VERIFICATION OF PROTECTION ZONES

Groundwater protection zones may be a key component of a WSP (see Chapter 16) for a given groundwater supply, and protection zones would typically be control measures in this context. This would subject them to operational monitoring for assessing whether or not the required restrictions on land use and controls of human activities are in place, and to verification for checking whether they are indeed effectively protecting groundwater at the point of abstraction. However, monitoring implementation and verification of water quality are equally important for supplies that are not using a WSP.

NOTE ▶ *The implementation of protection zones is effectively supported if the stakeholders involved collaboratively develop management plans that define their delineation and the activities allowed within zones, and that document monitoring procedures, which corrective actions should be taken both during normal and during incident conditions, and responsibilities, lines of communication as well as documentation procedures.*

The implementation of control measures to enforce compliance with protection zone requirements is substantially facilitated by an environmental policy framework (see Chapter 20).

Table 17.8 provides examples of control measures that may be used for protection zones, regardless as to whether or not this is done in the context of a WSP. It also includes suggestions for monitoring and verification of the example control measure given. For example, adequate protection zone delineation in order to protect the abstraction point from contamination with pathogens and/or chemicals could be validated by using tracer studies. Protection zone monitoring would focus on checking whether the required restrictions in land use and human activities are being adhered to. Groundwater quality monitoring in this context would serve to verify the efficacy of the specific protection zone concept, i.e. both its design and implementation.

NOTE ▶ *Options for monitoring suggested in Table 17.8 focus on the control measures rather than on groundwater quality.*

Comprehensive groundwater quality monitoring programmes are a supplementary aspect of monitoring with the purpose of providing verification of the overall efficacy of protection zones.

Table 17.8. Examples of control measures for groundwater protection zones and options for their monitoring and verification

Examples of control measures for protection zones	Options for their monitoring and verification
Define zone of protection for microbial quality, e.g. based on travel time and local hydrogeological conditions, vulnerability assessments or risk assessments	Conduct tracer tests (validation of delineation)
	Monitor land use and activities within zone to ensure compliance with use restrictions
	Verify protection efficacy with microbial indicators (faecal streptococci; *E.coli,* bacteriophages)
Define zone of protection for chemical quality, e.g. based on travel time and local hydrogeological conditions, vulnerability assessments or risk assessments	Conduct tracer tests (validation of delineation)
	Monitor land use and activities within zone to ensure compliance with use restrictions
	Verify protection efficacy with specifically selected potential contaminants
Define zones vulnerable to nitrate contamination	Monitor fertilizer (inorganic and organic) applications and manure applications, potentially also stock density
	Verify with chemical analysis
Control pumping to ensure effect of draw-down does not increase risks of leaching	Pumping tests to measure draw-down
	Monitor water levels around pumping wells with piezometers
	Audits of pumping
Prioritization of aquifers for protection zones	Priority of aquifers indicated on maps and reports
	Site inspection to verify compliance

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