Section IV

Approaches to drinking-water source protection management

16

Water Safety Plans: Risk management approaches for the delivery of safe drinking-water from groundwater sources

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The delivery of safe drinking-water requires actions to be taken throughout the water cycle from the catchment to the point of consumption. The focus of any programme designed to deliver safe drinking-water should therefore be the effective management and operation of water sources, treatment plants and distribution systems (whether piped or manual). This will demand action by water suppliers, environmental protection agencies and health bodies.

WHO (2004) outlines that the delivery of safe drinking-water is most effectively achieved a Water Safety Framework, that encompasses three elements:

1. Establishing health based targets for drinking-water based on evaluation of health concerns.
2. Developing a management system to meet these targets that is termed Water Safety Plan (WSP) and consists of

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- An assessment of the water supply system to determine whether the water supply chain (from source through treatment to the point of consumption) as a whole can deliver water that meets the health based targets.
- Identification and operational monitoring of the control measures in the drinking-water supply that are of particular importance in securing drinking-water safety.
- Preparation of management plans documenting the system assessment and monitoring plans and describing actions to be taken in normal operating and incident conditions, including upgrading documentation and communication.

3. A system of independent surveillance that verifies that the above are operating properly.

The establishment of health-based water quality targets would typically be led by the health sector taking into account local health burdens. These are not discussed in detail in this text, but would include many of the considerations highlighted in Section I and would be established in relation to a level of public health risk determined as being tolerable. This may use epidemiological and quantitative risk assessment procedures, which can be applied to both chemicals and microorganisms (Haas *et al*., 1999). More detail is available on establishment of water quality targets in the third edition of the WHO *Guidelines for Drinking-water Quality* (2004) and in Havelaar and Melse (2003).

The surveillance component would typically be undertaken by a regulatory agency, which in practice may be the health, environment or local government sector. This component would incorporate many of the issues identified in Sections II, IV and V of this monograph as means of monitoring of performance. Further descriptions of approaches to be used are available in a variety of texts linked to the WHO *Guidelines for Drinking-water Quality* (WHO, 1997; 2004; Howard, 2002).

The second activity of the Water Safety Framework is termed a Water Safety Plan (WSP) (WHO, 2004; Davison *et al.,* 2005) which is typically the responsibility of the water supplier, with support from and collaboration with other sectors as discussed below. The focus of this chapter is the application of WSPs within groundwater supplies and catchments. This covers both supplies where the whole WSP will apply to the groundwater, where the point of delivery is at the abstraction point (e.g. tubewell with handpump) and those where groundwater forms only part of the overall WSP (e.g. borehole connected to a distribution system). The principles and methods used in WSPs draw on other risk management and quality assurance methods. In particular they are based on the Hazard Analysis and Critical Control Process (HACCP) approach applied in the food industry.

As described by the multiple barrier principle, source protection is the first stage in the production of safe drinking-water quality (WHO, 1993; 2004). When sources are managed effectively, subsequent treatment costs are minimized and the risks of exposures resulting from failures in treatment processes are reduced. Therefore, source and resource protection is vital for efficient risk management (WHO, 2004). Protection measures should be put in place that have been shown to be effective in improving water safety as the first stage of a plan for managing the safety of drinking-water.

16.1 END-PRODUCT TESTING AND THE NEED FOR A RISK MANAGEMENT APPROACH

The traditional approach to water quality management placed a great emphasis on the routine monitoring of water quality. The results of analysis were compared against acceptable concentrations in order to evaluate performance of the water supply and to estimate public health risks (Helmer *et al*., 1999). The focus of attention was on end-product standards rather than ensuring that the water supply was managed properly from catchment to consumer. Although operation and maintenance of water supplies has been recognized as important in improving and maintaining water quality, the primary aim of water suppliers, regulators and public health professionals has been to ensure that the quality of water finally produced met these standards.

This reliance on end-product testing has been shown to be ineffective for microbial quality of water, as evidence has emerged of significant health impact from the consumption of water meeting national standards (Payment *et al*., 1991). In part this is because most national standards have been set using bacterial indicators that are very different from viral and protozoan pathogens.

The quality of the source protection measures is an important component in controlling whether pathogens may be present in the final drinking-water. For instance, one study concluded that the degradation of surface water catchments was an important factor in waterborne disease transmission (Hellard *et al*., 2001). The outbreak of *E. coli* O157:H7 and *Campylobacter jejeuni* from drinking-water in Walkerton, Ontario appears to have resulted from a combination of improper protection of the groundwater source and a failure to maintain adequate chlorination (O'Connor, 2002). The example from Walkerton particularly emphasizes the need for multiple barriers in water quality management.

End-product testing has a further weakness in that the number of samples taken is typically very small and not statistically representative of the water produced in a domestic supply. The focus on end-product testing has meant that action is only initiated in response to a failure in relation to the specified water quality standard. However, this typically means that the water has been supplied and may have been consumed before the results of the test are known and the increased risk to health identified. As a result, outbreaks occur and rates of endemic disease remain higher than when good practice in relation to water quality management is emphasized. The reliance on end-product testing is therefore not supportive of public health protection and whilst it retains a role in assessing water safety, it should not be the sole means by which risks are managed (WHO, 2004).

16.2 SCOPE OF WATER SAFETY PLANS

Water quality management elements such as documented operational procedures, monitoring process control measures and sanitary inspection have complemented end-product testing in many water supplies for a long time. Beyond these, the need for a comprehensive quality assurance approach based on sound scientific evidence and understanding the risks in a given supply system has been increasingly recognised.

Quality assurance procedures are being applied more formally to water supplies, including the use of HACCP and approaches based on the generic ISO 9000 Quality Standard.

The use of HACCP for water quality management was proposed by Havelaar (1994), following international codification of the principles for the food industry (Codex Alimentarius Commission, 1996; NACMCF, 1992). Subsequent initiatives have addressed the application of these principles to the broader control of infectious disease from water and wastewater exposures (Fewtrell and Bartram, 2001). The application of HACCP principles have also been further described in relation to specific water supplies (Barry *et al.*, 1998; Deere and Davison, 1998; Gray and Morain, 2000; Deere *et al.*, 2001; Bosshart *et al.,* 2003; Howard, 2003; Wülser and Trachsel, 2003). These experiences were used as basis for the Water Safety Plan approach in the third edition of the WHO *Guidelines for Drinking-water Quality*.

The development and implementation of a WSP would typically be the responsibility of a water supplier, although in many cases other stakeholders may have responsibilities that must be fulfilled. Such plans should address all aspects of the water supply under the direct control of the water supplier and focus on the control of water production, treatment and distribution to deliver drinking-water. In some situations, the water supplier will control the catchment and therefore will be able to identify and implement control measures within the catchment. In other situations, the water supplier may not control the catchment and therefore some aspects of control will require actions by other stakeholders. These may still be incorporated within the WSP provided that processes are set in place for communication of the findings of monitoring, and actions are identified in the case of non-compliance. In these situations, the implementation of a WSP provides a sound platform for the water supplier to take an active role in initiating and developing stakeholder involvement for the protection of drinking-water sources (Box 16.1).

WSPs can be defined for utility operated water supplies using mechanized boreholes, disinfection and piped distribution; or for simple point sources of water where water is collected by hand and transported back to the home manually (WHO, 2004). In the case of small water supplies, the WSP may be defined by an external agency and be applied either through a generic WSP for a technology type or be developed for an individual supply using very structured guidance (APSU, 2005; MOH NZ, 2001; SGWA, 2003; WHO, 2004). However, it will be expected that the activities required under the WSP will be the responsibility of the water supply operator.

Although this monograph deals with groundwater sources and their protection for public health, a key value of WSPs is that they address the full water supply chain from source to consumer. WSPs therefore demand action is taken in water sources and their catchments (whether groundwater or surface water), in treatment steps (if any are applied), subsequent distribution and household storage and treatment.

WHO (2004) identifies that the development of an effective WSP requires (Figure 16.1):

- assembling a team that understands the system and can undertake an initial assessment of the system with regard to its capability to supply water meeting the specified targets;

- identifying where contamination can occur and what measures can be put in place to prevent, reduce or eliminate contaminants (control measures);
- validation of methods employed to control hazards;
- putting in place a system for monitoring and corrective action to ensure that safe water is consistently supplied;
- periodic verification that the WSP is being implemented correctly and is achieving the performance required to meet the water quality targets.

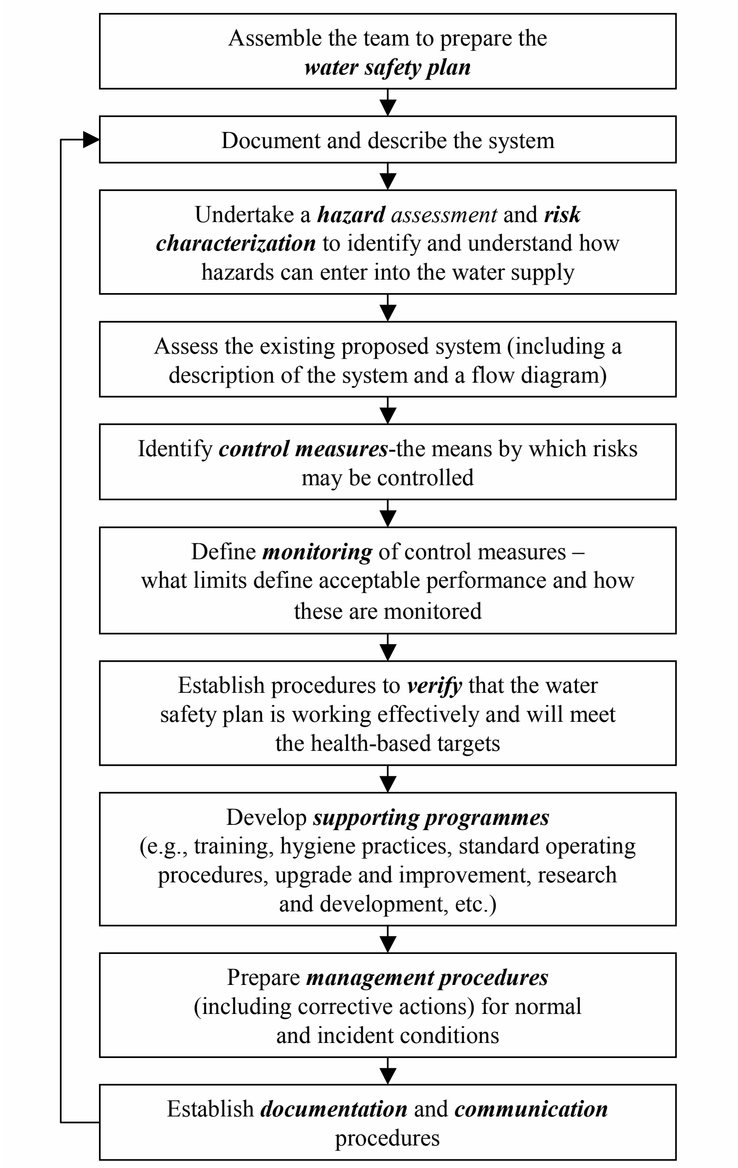


Figure 16.1. Steps in the development of Water Safety Plans (adapted from WHO, 2004)

16.3 PRELIMINARY STEPS FOR DEVELOPING WATER SAFETY PLANS

16.3.1 Assembling the team

The first stage of a WSP is to assemble a team of experts who will undertake the assessment of the water supply from catchment to consumer. This should be a multi-disciplinary team including managers, scientists (e.g. hydrogeologists, microbiologists, chemists) engineers (e.g. from operations, maintenance, design and capital investment) and technical staff involved in the day-to-day operation of the supply. The latter are essential as very often it is those members of staff who undertake work on the system every day who have the greatest knowledge about the problems that exist. A senior member of the team (usually the risk manager) should be appointed to help guide and direct the team in the study and this person should be able to either make decisions regarding investment or be able to influence others in the improvement of performance.

The development of the WSP and supporting programmes (which will typically involve actions by other stakeholders, such as environmental protection agencies) is generally most effectively implemented when the skills required are drawn from a range of stakeholders. For groundwater, this will include representatives of agencies responsible for assessing the impact of pollution and implementing controls on land-use. This may be particularly important when identifying control measures within catchments where the water supplier does not own the land. Thus the WSP team can act as catalyst for collaboration with different stakeholders and establish a sense of mutual ownership for controlling contaminants at their source.

16.3.2 Describing the water supply

The next stage in developing a WSP is to describe the water supply. In the case of groundwater supplies, this means providing information on aspects such as the depth to the water table, nature of the lithology of the aquifer and unsaturated zone from drilling logs, technologies used to abstract water, pump type and depth and the draw-down on pumping. This stage should also clearly identify whether alternative water sources exist in the community should there be need to take the source off-line at any time to effect corrective action.

The next step is to prepare a detailed flow diagram. The purpose of this stage is to provide the basis of understanding the hydrological environment and the subsequent distribution of drinking-water. The flow diagram should indicate the flow of water from the recharge to the abstraction point, the nature of the aquifer and recharge areas, flow times and vulnerability maps where available (Chapters 2 and 8 provide more detailed information on how the hydrological environment can be characterized). This stage is concerned with defining the hydrogeological conditions in order to understand what natural processes may affect the quality of water. The distribution of final water (whether piped or manual) should also be indicated on the flow diagram.

Two examples of simple flow diagrams – one for a simple setting with a shallow borehole and one for a more complex setting including treatment and piped distribution – are shown below in Figures 16.2 and 16.3.

Finally, the flow diagram is verified in the field. This will involve site inspection and for groundwater the use of conservative tracers and hydrogeological models. As groundwater flow is often complex, the process of verifying the flow diagram may be ongoing and it can be expected that the understanding of hydrogeological conditions will improve over time as more information becomes available.

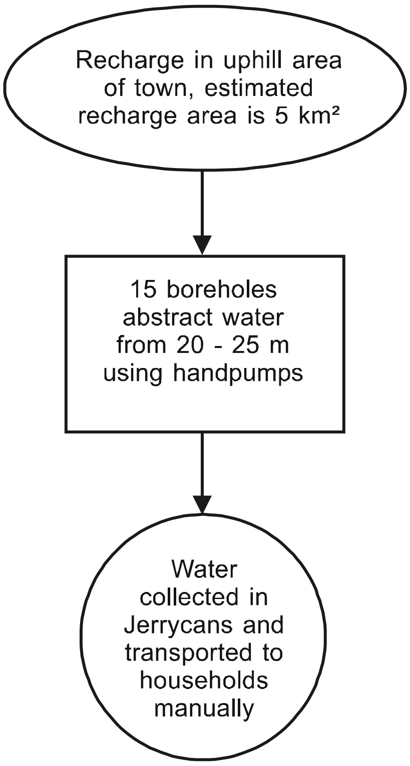
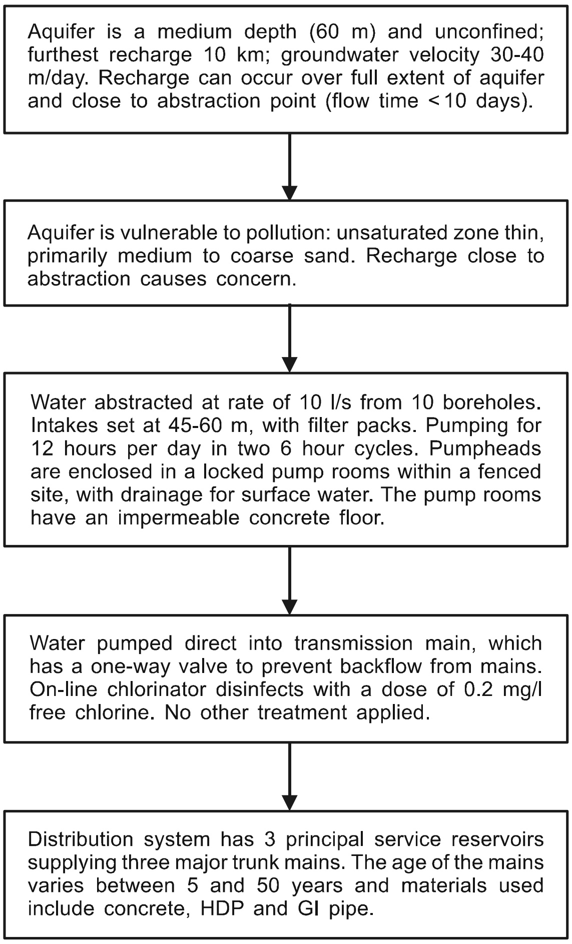


Figure 16.2. Simple flow diagram for small point water source

16.3.3 Identifying intended uses and vulnerability of the users

The intended use of the water supply should be defined to ensure that the requirements this may place on quality are incorporated into the WSP. In some cases, there will be more than one use for the water (i.e. domestic, industrial, irrigation) that may compete for allocation of resources where these are scarce. The WSP and supporting programmes should be clear in defining control in relation to drinking/domestic use. It is also important to consider whether there are particularly vulnerable groups using the water (i.e. immuno-compromised, elderly, infants) and to consider the socioeconomic conditions and vulnerability of different groups using the water. This will be linked to the development of the WSP and in particular relates to the hazard analysis and corrective actions.



Aquifer is a medium depth (60 m) and unconfined; furthest recharge 10 km; groundwater velocity 30-40 m/day. Recharge can occur over full extent of aquifer and close to abstraction point (flow time < 10 days).

Aquifer is vulnerable to pollution: unsaturated zone thin, primarily medium to coarse sand. Recharge close to abstraction causes concern.

Water abstracted at rate of 10 l/s from 10 boreholes. Intakes set at 45-60 m, with filter packs. Pumping for 12 hours per day in two 6 hour cycles. Pumpheads are enclosed in a locked pump rooms within a fenced site, with drainage for surface water. The pump rooms have an impermeable concrete floor.

Water pumped direct into transmission main, which has a one-way valve to prevent backflow from mains. On-line chlorinator disinfects with a dose of 0.2 mg/l free chlorine. No other treatment applied.

Distribution system has 3 principal service reservoirs supplying three major trunk mains. The age of the mains varies between 5 and 50 years and materials used include concrete, HDP and GI pipe.

Figure 16.3. Simple flow diagram for large groundwater abstraction linked to piped distribution

16.4 HAZARD ANALYSIS

Once the system has been described, a hazard analysis should be performed. A hazard is a biological, chemical, physical or radiological agent that has the potential to cause harm to health. The simplest method of undertaking a hazard analysis is to perform a sanitary survey or catchment assessment to identify all the sources of potential hazards. Chapters 9-13 of this book provide information on the likely hazards that will be derived from different polluting activities and sources of hazards as well as indicative checklists to help assess their relevance in a given setting. The sanitary survey or catchment assessment should lead to the preparation of a map that provides details on where water sources and sources of pollutants exist within the recharge area. An example of a map in a simple setting is shown in Figure 16.4.

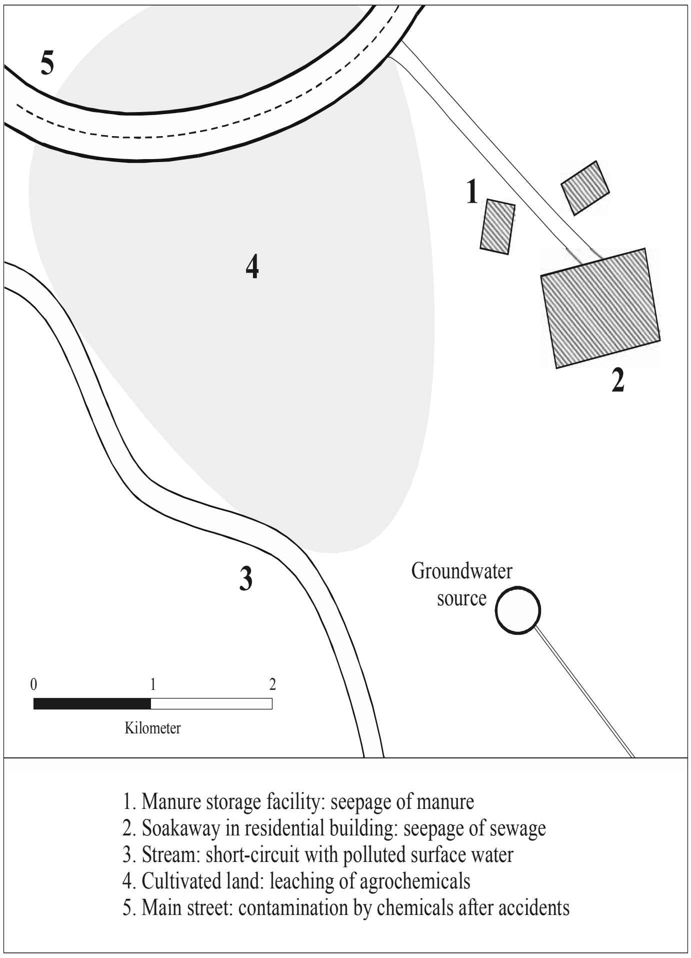


Figure 16.4. Simple map showing potential pollution sources to a small groundwater abstraction point (adapted from SGWA, 2003)

When undertaking a hazard analysis, it is often more effective to consider hazardous events rather than the specific hazards that affect the water supply. A hazardous event is an incident or situation that can lead to the presence of the hazard, and thus describes how a hazard could enter the water supply. For instance, a hazardous event could be that pathogens from human faeces enter groundwater from poorly constructed and sited septic tanks, or that hazardous chemicals leach into groundwater when spilled by accident at an industrial site. The advantage of using a hazardous event approach is that the probability of the event occurring can be considered, as the presence of a source of hazards within the drinking-water catchment area does not automatically mean that the hazards will be found at a groundwater abstraction point.

The probability with which hazards reach the aquifer depends on hydrogeological conditions as described in the concept of aquifer vulnerability in Chapter 8 and on their behaviour in the sub-surface as described in Chapters 3 and 4. By combining sanitary survey or catchment assessment data, vulnerability and pollutant behaviour the probability of occurrence of contaminants can be assessed (Chapter 14).

As discussed in Section 15.2, in groundwater the occurrence of hazards may not only be of an episodic (or event) nature but often is continuous and causes longer-term pollutant loading and attention should be paid to times scales. They may also be related to diffuse or multiple point sources rather than single point sources of hazards. Chemicals that are intentionally released to land over long periods of time that have the potential to accumulate in the aquifer, e.g. nitrate from fertilizers or manures and pesticides used in agriculture are examples of hazards that build up over time and from a diffuse area. In settings where the aquifer is moderately vulnerable to nitrate pollution, it is likely that controlled use of fertilizer in line with best management practices will not cause groundwater quality deterioration. In contrast, continuous over-fertilization in the same setting over years or even decades can cause heavy long-term nitrate pollution. For substances having the potential to accumulate in groundwater, the definition of hazardous events (e.g. over-fertilization) is always also related to the protection of future source water safety, as the present situation may not result in short term deterioration of water quality.

For natural chemical constituents affecting human health (e.g. arsenic and fluoride), the hazard analysis should include an assessment of the geological setting to evaluate whether it is likely that there will be any naturally occurring chemicals present at levels that will pose a risk to public health. The potential impact of land use on mobilization of chemicals should also be considered at this point. An initial comprehensive water quality assessment remains a further essential component of the hazard assessment for chemicals.

The hazard analysis will direct subsequent stages of Water Safety Plan development to ensure that control measures are managed, upgraded or put in place in such a way that they will effectively control identified hazards. Undertaking hazard analysis and assessing the risk posed by the hazards identified is essential: simply applying control measures without considering which hazards are the most important will mean that risks posed by some hazards are likely to remain high and resources will be wasted in controlling hazards that may be irrelevant for the specific water supply.

16.5 SYSTEM ASSESSMENT

The system assessment stage of the WSP development uses the information gained in the system description and hazard analysis in order to assess the risk of hazards occurring in drinking-water, and the potential of the system to control them. It is a first step in determining whether the water supply is able to meet the health based targets or other water quality targets defined for the water supply and if not, what investment of human, technical and financial resources would be required to improve the supply.

System assessment is largely the subject of this book, with Section II introducing the hazards, Sections IV and V the control measures and Section III discussing how to combine information for assessing the risk of hazards occurring in groundwater. The following section revisits this in terms of using these to develop a Water Safety Plan.

System assessment in the WSP-context will include further barriers such as treatment that determine whether the risk can be controlled.

For example, if a borehole abstracts water from a deep aquifer that has a significant unsaturated zone, limited human development over the aquifer and the potential to use legislation to control activities, the system is likely to be capable of meeting established targets and control measures in the catchment can be identified. In this case, the system assessment has not shown the need for any significant upgrade. By contrast, if a borehole abstracts water from a karstic aquifer where there is extensive human development over the aquifer and no disinfection, the system may not be able to meet the targets without investment at least in a treatment step at the borehole. This example illustrates when a systems assessment will identify that an upgrading of the system is required and the investment needs. The system assessment, therefore, may identify immediate investment requirements essential for meeting the targets. It is unlikely that all control measures will require substantial infrastructure improvements and therefore even in situations where improvements are needed, some readily implemented control measures can be identified, monitored and managed.

Risk assessment and prioritising hazards for control

The definition of control measures should be based on a ranking of risks associated with the occurrence of each hazard or hazardous event. Section 14.2 of this book discusses how to assess the potential for contaminants to occur in groundwater. However, in context of developing a Water Safety Plan, prioritising hazards will be more comprehensive and will involve the assessment of hazards in whole supply system, including steps after the abstraction of groundwater (such as disinfection and distribution). A more generic approach to assessing risks and prioritising hazards is therefore briefly introduced here.

Risk is the likelihood of identified hazards causing harm in exposed populations in a specified time frame, including the magnitude and consequence of that harm. Those hazardous events with the greatest severity of consequences and highest likelihood of occurrence should receive higher priority than those hazards whose impacts are mild or whose occurrence is very uncommon.

There are a variety of means by which prioritization can be undertaken, but most rely on applying expert judgement to a greater or lesser degree. The approach discussed below uses a semi-quantitative risk scoring matrix to rank different hazardous events. This approach has been applied in risk assessment, and specifically for drinking-water in Australia and Uganda (Deere *et al.*, 2001; Godfrey *et al.*, 2003); similar approaches have been used in other countries, such as New Zealand and Switzerland (SGWA, 1998; MOH NZ, 2001).

Within this approach, severity of impact is categorized as three major types of event: lethal (i.e. significant mortality affecting either a small or large population); harmful (i.e. morbidity affecting either a small or large population); little or no impact. Table 16.1 shows the definition of a set of variables for likelihood/frequency of occurrence and combined severity/extent assessment with appropriate weighting of variables. Table 16.2 indicates the final overall score of all possible combinations of the conditions. Table 16.3 gives an example of that approach for a scenario in an alluvial aquifer.

Table 16.1. Examples of definitions of hazardous event terms that can be used for risk scoring (modified from WHO, 2004)

Description	**Definition**	**Weighting**
Likelihood or frequency of occurrence		
Almost certain	Once per day	5
Likely	Once per week	4
Moderate	Once per month	3
Unlikely	Once per year	2
Rare	Once every 5 years	1
Severity of consequence or impact		
Catastrophic	Potentially lethal to large population	5
Major	Potentially lethal to small population	4
Moderate	Potentially harmful to large population	3
Minor	Potentially harmful to small population	2
Insignificant	No impact or not detectable	1

Table 16.2. Example of a simple risk ranking matrix (modified from Deere *et al.*, 2001 and WHO, 2004)

Likelihood or frequency of occurrence	**Severity of consequence or impact**				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	5	10	15	20	25
Likely	4	8	12	16	20
Moderate	3	6	9	12	15
Unlikely	2	4	6	8	10
Rare	1	2	3	4	5

While some approaches use a scoring method as indicated by the numbers in Table 16.2 others prefer non-numerical classifications describing the risk (as indicated by the shading; see also Table 15.2 in Chapter 15). It should be stressed that when using the scoring approach it is the relative ranking based on the numerical categories rather than the numbers themselves that is important. Furthermore, in using such approaches common sense is important to prevent obvious discrepancies arising from applying the risk ranking, for instance events that occur very rarely but have catastrophic effects should also be a higher priority for control than those events that have limited impact on health, but occur very frequently.

The risk ranking approach allows the relative importance of different hazardous events to be systematically evaluated. This supports decision makers to define priorities for control within their water supply and can therefore maximize the cost-effectiveness of the WSP.

The outcome of system assessment is an identification of priorities for controlling risks, of existing control measures that have been found to be of importance for controlling risks, and of gaps in safety for which new control measures need to be identified or existing ones upgraded.

Table 16.3. Example of hazardous events identified and assessed for an alluvial aquifer

Process step	Hazardous event	Hazard type	Likelihood	Severity	Risk score
Alluvial aquifer	Water pumped during a storm event results in contaminated surface water from catchment run-off being drawn into aquifer	Microbes and chemicals (nutrients and potential pesticides from agricultural practices)	Unlikely (2)	Catastrophic (5)	10
	Cattle grazing near wellhead and rain events result in contaminated surface water entering the wellhead	Microbes and chemicals (mainly nutrients)	Moderate (3)	Catastrophic (5)	15
	Draw down of aquifer causing naturally occurring chemicals to enter water	Chemicals	Rare (1)	Major (4)	4

16.6 CONTROL MEASURES

In the context of a Water Safety Plan, control measures are tightly defined as those steps in drinking-water supply that directly affect drinking-water quality and that collectively ensure that drinking-water consistently meets health-based targets. Therefore, they are the basis on which control is assured and therefore they should always function reliably. Control measures are activities and processes applied to prevent hazard occurrence within the water supply chain or at the pollutant source, which control the risk posed by the hazards or hazardous events identified on a continuous basis. Examples of control measures for groundwater protection are provided in Chapter 17, for the immediate protection at the abstraction point in Chapter 18, for hydrological management in Chapter 19 and for specific polluting activities in Chapters 21-25.

Control measures in groundwater sources can take one of two forms:

- those that use natural attenuation processes to reduce or remove/inactivate pollutants (e.g. adsorption, filtration, predation, microbial degradation, die-off);
- those that prevent or reduce pollution of the aquifer's recharge area or ingress of pollutants into the water supply.

Measures such as groundwater protection zones (Chapter 17) and hydrological management (Chapter 19) combine both forms of control measure. In these cases, release of pollution within recharge areas is controlled (although often not entirely prohibited) within prescribed areas related to the time taken to travel to the water abstraction point, and rely on attenuation, die-off and hydrodynamic dispersion to achieve reductions in pollutant loads. When protection zones are used, there may be extensive control on specific activities such as restriction on traffic, settlements, agricultural activity and other human activity as discussed in Chapter 17.

Measures such as wellhead and sanitary completion discussed in Chapter 18, and avoidance, reduction and treatment of pollutants at their source described in Chapters 21-25, represent the second type of control measure. These are all designed to prevent contamination from either entering the supply or being released into the environment rather than relying on natural processes to remove or reduce pollutants.

The control measures should be able to influence the quality of groundwater and to be amenable to control through action, preferably by the water supplier. For instance, rainfall often exerts a profound influence on shallow groundwater and numerous studies have shown that rainfall is a principal factor in water quality deterioration (Wright, 1986; Gelinas *et al.,* 1996; Howard *et al*., 2003). Rainfall cannot be translated into a control measure because action cannot be taken directly to reduce rainfall. A series of control measures can be defined, however, that relate to the importance of rainfall in causing contamination. For example these would include providing diversion ditches to prevent inundation of the abstraction point by contaminated surface water, maintaining infrastructure integrity at the abstraction point and controlling pollutant releases through the use of protection zones. Details of required measures are outlined in Chapters 17 and 18.

WHO (2004) note that control measures included within the WSP should have the following basic characteristics:

- a monitoring system and operational limits can be defined that describe the performance of the control measure and which can be either directly or indirectly monitored;
- corrective actions can be identified as a response to deviations in control measure performance that are detected by monitoring;
- corrective action will protect water safety by ensuring that control is re-instated (this can be bringing the control measure back into compliance, enhancing the control measure or by implementing additional control measures);
- detection of deviations and implementing corrective actions can be completed sufficiently rapidly to prevent the supply of unsafe water.

Control measures should not be vague or imprecise as otherwise the management action to be informed from the assessment of control status will be difficult to define. For instance, control of agricultural pollution in a catchment may be a general control measure, but would need to be translated into a set of specific actions, such as a seasonal restriction on the application of fertilizers and manure, and restriction on feedlots within a specified distance. An example for controlling nitrate pollution in groundwater from agriculture by means of integrating the water supplier's WSP and the activities of a Regional Nitrate Committee in Switzerland is given in Box 16.1.

Individual control measures will usually be designed for a specific hazardous event(s) but it is unlikely a single control measure will provide assurance for all hazardous events and situations; rather a suite of different control measures may be necessary. Table 16.4 below provides examples of likely control measures appropriate to groundwater sources.

Many of the control measures for groundwater protection may have to be implemented through the relevant stakeholders rather than by the water supplier. The water supply agency, however, may take the lead as part of the WSPs supporting programmes (see Section 16.10) in initiating specific controls in order to protect the quality of the drinking-water source.

Box 16.1. Measures for controlling nitrate pollution from agriculture in the Lenzburg water supply

The municipality of Lenzburg, Switzerland as well as the surrounding municipalities, draw drinking-water from the same groundwater recharge area. Each municipality operates its own abstraction wells. Part of the area upstream of the abstraction zone is used for agriculture, and the rest of the upstream area is covered by forest. Due to over-fertilization by agriculture, high nitrate concentrations were measured at all abstraction wells in the recharge area. These nitrate concentrations increased from 15 mg NO3/l in the early 1960s towards the Swiss drinking-water standard of 40 mg NO3/l by the early 1980s.

The Nitrate Committee: On the initiative of the Lenzburg water supply (LWS), all municipalities that were affected by increasing nitrate concentrations in drinking-water, or that encompassed large areas with agricultural use in the recharge area, collectively formed a Regional Nitrate Committee in 1987. Each municipality appointed one district council representative plus one local farmer as members of the Committee. In addition, a professional advisor from each of the Cantonal Water Authorities and the local Agricultural Advice Centres, plus a geologist, were co-opted to provide support to the Committee. The Nitrate Committee is chaired by the LWS. All costs that result from the committee's activities are shared between all the municipalities involved according to a pre-established formula.

N-min measurements: The Committee as its first activity organized public advisory consultations for local farmers. In parallel, a nitrate regulation was elaborated that did not come into force in the municipalities involved but was set up as a target to be met by farmers on a voluntary basis. The regulation included detailed maps at the single plot scale showing the results of soil analyses and N-min measurements. N-min values represent the amount of plant-available nitrogen at the beginning of the vegetation period, and therefore provide the basis for defining an adequate amount of fertilizer to be applied. N-min measurements are repeated every year, and the results are made available to farmers, in conjunction with fertilization recommendations for individual crops, through the Agricultural Advice Centre. All samples, measurements and advisory consultations are funded through the Nitrate Committee and are therefore free of charge for the farmers.

Subsidies for intercropping: As nitrate leaching occurs mainly between seasons when fields lie fallow between two crops, the Committee recommended and supported intercropping with nitrogen binding cover crops. If farmers fulfil specific pre-conditions, such as prohibitions of tillage operations for a limited time period, minimum duration of intercropping depending on the rotation of crops, data recording by means of a field calendar, and use of recommended intercropping species, then the Committee supports those activities by paying intercropping subsidies per cultivated area unit, i.e. 400 Swiss Francs per ha in 2003. The plot-tailored fertilization together with intercropping has stopped the trend of increasing nitrate pollution of the aquifer, e.g. nitrate concentrations declined to 25-30 mg NO3/l in 2003.

Municipality liaison: The role of farmer representatives in the Nitrate Committee is of great significance because they liaise between the farming community and the Committee, and thus with the LWS. On the one hand they represent the farmers' interests to the Committee. On the other hand they have a duty to advise their farming colleagues in the municipality of the recommendations of the Committee. Furthermore, they have to check whether the statements made by farmers in their applications for intercropping subsidies are valid, and whether all pre-conditions have been fulfilled. If the liaison person approves each farmer's application, then the Nitrate Committee will pay the subsidies for intercropping.

Lenzburg's Water Safety Plan: The WSP of the LWS identifies long-term nitrate accumulation in the aquifer as a priority hazard. However, the LWS cannot exert direct control on polluting activities by farmers, as it does not own the farmland in the recharge area. Therefore the WSP explicitly refers to the activities of the Nitrate Committee, i.e. controlling nitrate pollution (through fertilization recommendations and granting subsidies for intercropping), monitoring compliance with those control measures, and imposing sanctions to farmers in case of non-compliance (corrective action). Additionally to the integration of the Committee's activities into the WSP, LWS carries out six-monthly inspections of the recharge area as means of verification that control system works effectively.

Table 16.4. Examples of control measures to protect the quality of drinking-water

Element	Control measure
Wellhead completion	Sanitary seal (prevention of direct ingress) Fencing around area Surface water diversion ditches Quality of concrete works Wastewater drainage
Land use planning	Protection zones (designated and limited uses, protective requirements) Control of human activities within drinking-water catchment Set-back distances Minimum safe distance (latrine-source) Animal access control Grass cover maintained in immediate area

16.6.1 Validation of control measures

Validation is an essential component of a WSP. Validation is an investigative activity to assess the effectiveness of individual and combinations of control measures in reducing the risk posed by hazards or hazardous events. It therefore obtains evidence on the performance of control measures and ensures that the information supporting the WSP is correct. In some cases, the performance of an individual control measure may depend in part on the performance of another previous control measure and this must be borne in mind when defining performance criteria. This reflects the multiple barrier principle that is advocated as part of effective risk management of drinking-water quality.

The efficacy of each control measure in reducing or eliminating the risk of exposure to pollutants should be measured directly against the hazard that it is designed to mitigate. This requires a research stage where the performance of the control measures, individually and in combination, is rigorously evaluated with regard to the hazards they are expected to control. This stage can be undertaken in a variety of ways and in many cases it is best to utilize all four. These are:

- evaluation of existing literature (including Chapters 3 and 4 of this book) to determine recorded survival, attenuation and dilution of pollutants in the type of groundwater to be utilized;
- rigorously designed field assessments of water quality and influences on quality;
- laboratory experiments using model groundwater;
- modelling of pollutant transport in groundwater.

In many cases, the existing literature (including this book) provides much of the information required to define control measures. However, as local conditions may vary significantly from those reported in the literature, the use of well-designed field assessments is often an effective way of gaining additional information to suit local conditions. Such assessments should be based on intensive assessment of a representative sample of water sources and evaluate data in order to define the importance of different factors in causing contamination (Howard *et al*., 2003). Where quality is poor, making improvements in the water sources or in reducing a pollutant source can also provide a useful way to measure efficacy.

The selection of parameters undertaken in such an assessment should relate to the principal pollutants of concern. For chemicals, this process is relatively straightforward as the substances of concern can be analysed and system performance in elimination therefore be validated. For microbial quality, it is preferable for validation to be based on assessments of control measures in relation to pathogens. It may be difficult to undertake analysis of a wide range of pathogens and therefore validation may focus on a small number of representative pathogens whose control would provide confidence that all pathogens of a similar nature would also be controlled. However, it may be necessary to undertake evaluations using indicator organisms as described in the example from Uganda in Chapter 18. Wherever possible, the range of microorganisms should reflect the range of likely pathogens. These may include *E. coli* and faecal streptococci as faecal indicator bacteria, bacteriophages as index organisms for viruses and spore forming bacteria as process indicators (Ashbolt *et al*., 2001). The primary purpose when using such organisms is to assess the impact of the control measures on the levels of the organisms and to use the resulting information on reductions as an indication of the likely impact of the control measures on pathogens. The criterion for their choice therefore is their similarity in retention by control measures as compared to groups of pathogensin order to indicate system performance in pathogen removal.

The outcome of validation is an assessment of how well the control measures in place or envisaged for introduction are likely to meet the heath based targets. This may include identifying the need for system upgrade as well as particular emphasis on monitoring and maintenance of control measures identified as being key to safety of a given supply system.

16.6.2 Establishing operational limits

For each control measure, operational limits of performance should be defined. These are quantifiable levels of performance that provide an indication of whether the control measure is functioning correctly (in compliance) or is not providing effective control (out of compliance). The operational limits for each control measure should be identified during validation, and their definition should be based on sound science but also take into account practical considerations regarding limits of detection and ease of measurement. Of utmost importance is ensuring that the operational limit is related to an action that can be taken to bring the control measure back into compliance.

Operational limits may be upper limits, lower limits or an envelope of performance measures and are typically simple process indicators that can be interpreted at the time of monitoring and where action can be taken in response to a deviation (WHO, 2004). For instance, a groundwater protection zone may be defined as a control measure and within this zone the discharge of faecal material from sanitation facilities is strictly controlled. The operational limits in this case will be the absence of sources of faecal material (e.g. from septic tanks or pit latrines) within the protection zone. If a new on-site sanitation facility is constructed within the protection zone, the operational limit is exceeded and therefore corrective action should be taken to remove the facility or ensure that the design prevents contamination from occurring. The results of monitoring in relation to this operational limit (e.g. presence or absence of on-site sanitation facilities) can be interpreted immediately on observation and a clear line of action can be defined in response to the deviation.

Control measures may also be defined related to pumping rates if it has been shown that the draw-down would substantially alter the protection zone above a certain level of pumping. In this case, the operational limit will relate to the pumping regime (possibly both in terms of allowed discharge and in terms of duration of pumping). Other operational limits that can be defined would include stock density in relation to risks of increased nitrate (Chapter 21) and simple measures of wellhead or sanitary completion related to drainage (Chapter 18).

When defining operational limits, it is important to avoid situations where exceeding the operational limit will result in immediate health risks. It is better to establish operational limits that are more conservative and still allow preventative actions to be taken. If operational limits cannot be defined, it is likely that the measure identified should be considered as being part of a supporting programme. For some control measures, further limits may be established as ‘critical’ limits at which exceedance represents a confidence in water safety is lost and urgent action is required. Such limits tend to be related primarily to treatment processes, for instance disinfection, rather than source protection measures.

16.7 OPERATIONAL MONITORING

Operational monitoring assesses the performance of control measures at appropriate time intervals. It is essential within WSPs to ensure that the control measures employed remain in compliance with the operational limits. An emphasis is placed on simple techniques , which describe process controls that allow rapid, and easy measurement and whose findings can be interpreted at the time of monitoring with actions identified in response to non-compliance (WHO 2004; Davison *et al.*, 2005). Examples of monitoring parameters include turbidity control to sanitary inspection (Howard *et al.,* 2001; Payment and Hunter, 2001). This requirement for operational monitoring means that the analysis of indicator organisms would not be included as monitoring parameters, although they would be used in verification (see Chapter 16.12). By contrast, for chemical hazards it may be appropriate to test for the substance of concern if the results is available within sufficient time to allow for corrective action before hazard break-though, although the analytical method may be different from that used for verification.

Operational monitoring should be able to quantify changes in performance of the control measure in relation to the operational limits and is therefore linked directly to process control or management actions prior to an increase in the risk posed by a hazard. Selection of monitoring parameters should relate to their reliability and sensitivity in estimating performance of the control measure in relation to the operational limits. The frequency of monitoring will depend on the nature of the control means and may in some circumstances be continuous and on-line, whilst in others may be relatively infrequent. In the case of groundwater sources, much of the monitoring will be based on inspection of controlled activities in the catchment area (Box 16.1) and the integrity of sanitary completion measures, rather than routine water quality testing.

Monitoring may include testing for specific water quality parameters. This may be on the source water or within the catchment area or surrounding specific pollution activities, for instance around mine tailings or landfills. It will be important to define whether monitoring should be of the pollutants of direct concern or whether sentinel chemicals or other properties of water can be used as surrogates. This may in some cases include monitoring of water levels or redox conditions if this will provide good information about increases in contamination risks.

Where water quality parameters are included in monitoring (for instance nitrate in relation to agricultural pollution or inorganic chemicals derived from landfill leachate) it is unlikely to be continuous and will be determined in relation to their adequacy for monitoring the control measure in specific settings. In each setting, monitoring may become more targeted during times of known elevated risk (e.g. seasonal influences on nitrate release). In some settings however, monitoring of such parameters may be very frequent for instance where aquifers are highly vulnerable and have rapid transit times, thus allowing very short time periods for corrective actions.

In summary, the indicators used in operational monitoring systems should be:

- *specific* – the indicator should relate to a particular control and not to a broad set of interrelated factors;
- *measurable* – it should be possible to translate the control status into some form of quantifiable assessment, even if data collection is based on semi-quantitative or qualitative approaches;

- *accurate* – the indicator must provide an accurate reflection of the control measure status in relation to the operational limits and be sensitive to changes that are of relevance and changes that may lead to exceeding the water quality targets;
- *reliable* – the indicator should give similar results each time it is measured;
- *transparent* – the process of selection of the monitoring indicator, the method and frequency of measurement and the interpretation of the results should be transparent and accepted by all stakeholders.

16.8 CORRECTIVE ACTIONS

Effective management implies definition of actions to be taken in response to variations that occur during normal operational and incident conditions. Such corrective actions should be defined for each control measure and documented in the WSP. Corrective actions are those interventions that will be undertaken in immediate response to control measures moving outside the operational limits defined. It is important that when developing the WSP such corrective actions are identified from the outset. Identification of corrective actions should not wait until a failure has occurred as this defeats the objective of risk management. However, lessons learnt from incident conditions may lead to improvement of corrective actions and thus these will not be static. Equally, corrective actions may also be refined based on experiences from other water supplies.

Corrective actions may be simple operational interventions, for instance if an inspection identifies problems with the fence or deterioration in concrete protection works around a borehole, immediate action should be taken to effect repairs. It may also involve more complex enforcement processes, for instance if stock densities are seen to increase in the catchment area, then action should be initiated to ensure that farmers reduce these (for instance through legal notices). They may involve interventions that are not possible to implement immediately or that will take some time to take effect, for example when there has been an accidental spill of chemicals that has reached the aquifer and which will require remediation through pumping and treating.

Corrective actions may include longer-term action, for instance the redefinition of groundwater protection zones as more information becomes available regarding groundwater flow and pollutant movement. In some cases, the corrective action may be limited to an increase in monitoring of a specific contaminant. For instance, if leaching from mine tailings or landfills has increased but the consequences are as yet unknown, it may be appropriate to install a monitoring network to monitor movement and behaviour in the first instance to determine whether further action is required.

Corrective actions may also include closing down a particular abstraction point until the contamination has been effectively removed or has passed through the aquifer. However, this option should only be considered when there are alternative water supplies available. If the description of the water source concludes that there is no viable alternative to the groundwater source, then it is essential that other corrective actions (e.g. treatment) can be implemented immediately to prevent public health risks.

Where a public health risk from contamination occurs despite the presence of control measures, this implies that further control measures must be defined and implemented.

This will involve investigating the cause of the contamination leading to the public health risk and from this data defining a set of new control measures to combat this risk. It should be noted that it is likely that new risks will be identified over time, and these should be assessed by periodic system validation (see Section 16.6.1). Furthermore, levels of tolerable risk and the health-based targets established may change.

16.9 VERIFICATION

Verification is a separate process to operational monitoring. It provides a final check on the overall safety of the drinking-water supply chain. Verification is not designed to be a routine frequent assessment but a periodic evaluation of the performance of the WSP as a whole. For utility supplies, verification is undertaken by the water supplier as well as independently by the surveillance agency. For community-managed water supplies, verification is likely to only be undertaken by the surveillance agency. Verification will typically involve a number of actions including audit of the implementation of the WSP and water quality analysis.

Audits of WSPs are designed to assess whether these have been appropriately designed, documented and implemented. As part of a typical audit, the records of monitoring and actions taken to ensure control is maintained are reviewed by inspectors who also inspect the infrastructure and results of monitoring to ensure that the WSP is being adhered to. Such audits will also typically assess whether communication (both within the supply organization and to regulators and users of the water) have been undertaken in a timely and appropriate manner following guidelines set out in the WSP. Audits can be equally applied to utility supplies (when internal verification will also be assessed) or community-managed supplies. In the latter case, the audit is likely to use different tools but still focus on whether the monitoring is being performed appropriately, whether control measures are functioning and whether this information is shared within the community. Water quality analysis is also likely to be included within verification programmes. Analysis of microbiological indicators is retained in such approaches, but would be undertaken less frequently than in systems relying largely on end-point testing. The range of microorganisms would be expected to increase to take account of the diversity of pathogens being controlled, yielding information of greater value in assessing performance of water quality management measures (Ashbolt *et al*., 2001).

Careful consideration should be given to the selection of the indicator organisms used for verification. *E. coli* remains the indicator organism of choice (WHO, 2004) and in many situation thermotolerant coliforms can be used as a surrogate. However, where possible other indicator organisms should also be considered used. Other indicators include faecal streptococci, and bacteriophages. It may also be of value to undertake tracer studies in order to verify whether the land use control measures will provide adequate protection. This could also be linked to hydrogeochemical models and contaminant propagation models where these are adequately calibrated and reliable.

Chemical testing may be included both in monitoring and verification, but the techniques used may vary depending on the objective of the testing. The parameters used in verification should be evaluated at the same time as validation in order that they can be calibrated against an acceptable risk of exposure. Verification is likely to include periodic analysis of the presence and concentration of substances in groundwater. This may be done at the source, within monitoring networks established around the abstraction point or monitoring around the sources of pollution. The design of appropriate sampling networks is critical and should provide sufficient detailed information to ensure that preventative actions can be deployed in a timely manner.

16.10 SUPPORTING PROGRAMMES

In addition to process control measures put in place to assure safety, further activities are required in order to ensure that safe drinking-water can be assured, including activities which have to be undertaken by institutions and agencies other than the water supplier. These supporting programmes are as essential to the delivery of safe drinking-water as are the control measures and monitoring identified in the WSP.

There are a number of types of supporting programmes, some examples are:

- a water supplier's documented policy and commitment to provide high-quality water supplies;
- appointment of a senior member of staff as the risk or water safety manager who is responsible for ensuring the safety of drinking-water produced;
- establishment of internal allocation of roles and responsibilities for assessment and management of risks;
- established internal communication strategy within the utility to ensure information from monitoring is acted upon promptly and appropriately;
- training provided to community operators;
- design and construction codes of practice as well as codes of good hygiene practice established and enforced;
- information exchange with regulators and other stakeholders;
- a risk communication strategy to provide information to the public in times of elevated risk;
- customer complaint procedures;
- implementation of Good Laboratory Practice, including calibration of monitoring equipment;
- staff training and awareness programmes;
- securing stakeholder commitment to the protection of groundwater;
- development of training and education programmes for communities whose activities may influence source water quality;
- establishment of collaboration contracts with farmers or farmers' associations (which may include financial incentives);
- training of catchment inspectors;
- mapping of catchment characteristics (e.g. land use; vulnerability; protection zones).

The proper implementation of supporting programmes is essential for effective control of public health risks from water supplies and should be accorded adequate priority.

In situations where the water supplier does not own the land that forms the catchment, and thus has no direct control over activities in it, many control measures related to source protection may become part of the supporting programmes. Specific examples may include, but are not limited to:

- development and implementation of catchment management plans;
- controlled density of stock in pastoral areas;
- controlled application of fertilizers and pesticides in the catchment;
- controlled access for the general public to pollution-sensitive areas in the catchment;
- development of groundwater quality models.

16.11 DOCUMENTATION

The final part of the development of the WSP is to document the process, considerations and criteria leading to assessments, and to ensure that people responsible for implementing the WSP have a point of reference. Documentation is also important as part of monitoring the effective implementation of the WSP. Therefore record keeping of monitoring and actions taken is an essential component of the plan.

Tables 16.5 and 16.6 provide examples of WSPs, one for a mechanized borehole and one for a tubewell fitted with a handpump. These WSPs are generic and are designed to provide the reader with a view of the type of material that may be developed. They are not designed as finished plans for immediate implementation, but as a framework within which WSPs can be developed. More detailed descriptions of WSPs may be found both in Water Safety Plans: Managing drinking-water quality from catchment to consumer (Davison *et al*., 2005) and the *Guidelines for Drinking-water Quality*, third edition (WHO, 2004).

Table 16.5. Model Water Safety Plan for mechanized borehole (based on Davison *et al.*, 2005)

Hazardous event	**Cause**	**Risk**	**Control measure**	**Operational limits**		**Monitoring**			**Corrective action**	**Verification**
				Target	*Action required if*	*What?*	*When?*	*Who?*		
Ingress of contaminated surface water directly into borehole	Poor well-head completion	Unlikely/ major	Proper wellhead completion	1 m concrete apron around wellhead Lining extends 30 cm above the apron Drainage ditches in place	Lining stops at ground level Apron damaged or cracked Ditches full, faulty or absent	Sanitary inspection	Monthly	Operator	Extend lining Repair apron Clean and repair drainage ditches	Sanitary inspection *E. coli* Faecal streptococci Bacteriophages
Ingress of contaminants due to poor construction or damage to the lining	Poorly maintained wellhead completion	Moderate/ major	Proper wellhead completion	Top 5 m of the annulus sealed Rising main in good condition	Annulus sealed for less than 3 m Colour changes Increased pumping required to raise water	Sanitary inspection Water clarity CCTV	Monthly	Operator	Insert seal around annulus Replace worn and corroded rising mains Use materials less likely to corrode (e.g. plastics)	Sanitary inspection Analysis of colour, iron and turbidity CCTV
Borehole area is inundated with contaminated surface water	Lack of diversion ditches	Unlikely/ major	Good drainage around wellhead	Diversion ditches of adequate size, in good condition and clear of rubbish	Ditch has rubbish or shows signs of wear	Sanitary inspection	Weekly	Operator	Repair and clean ditch Increase size of ditch using	Sanitary inspection
Pumping leads to increased leaching of contaminants	Pumping induces increased leaching of chemicals	Unlikely/ moderate	Pumping regime	Leaching of contaminants is within predicted range	Evidence of increased leaching of contaminants	Monitoring of key contaminants of concern Hydrochemical models	Monthly	Operator	Modify pumping regime Treatment	Hydrochemical models Monitoring contaminants of concern

Hazardous event	**Cause**	**Risk**	**Control measure**	**Operational limits**		**Monitoring**			**Corrective action**	**Verification**
				Target	*Action required if*	*What?*	*When?*	*Who?*		
Contaminated shallow water drawn into aquifer	Hydraulic connection exists between shallow and deeper aquifers allowing draw-down into deeper aquifer	Almost certain/ moderate	Control pumping regimes Set intake at depth	No evidence on induced leakage	Evidence of shallow water drawdown (e.g. shallow wells start to dry up)	Colour (appearance) Taste Odour Electric conductivity	Weekly	Operator	Set intake deeper (microbes) Water treatment (microbial) or blending (chemicals)	*E. coli* Faecal streptococci Bacteriophages Nitrate Tracer studies Hydrological models
Rapid recharge by rivers, streams and ponds	Hydraulic connection exists between surface water and aquifers	Unlikely/ major to catastrophic	Set intake at greater depth	Rapid recharge does not occur or cannot reach intake	Evidence of rapid recharge from surface water bodies	Surface water levels Colour Electric conductivity	Daily	Operator	Set intakes at greater depth or modify pumping regimes	*E. coli* Faecal streptococci Bacteriophages Pathogen assessments Nitrate
Pumping increases safe distances beyond current protection zone boundaries	Pumping increases cone of depression extends minimum travel time distance beyond protection zone	Unlikely/ moderate	Protection zones	Protection zones include influence of drawdown on groundwater flow	Drawdown increases distance equivalent to travel time set	Water table levels surrounding borehole when pumping	Annual	Operator	Extend ground-water protection zone to account for the change in distance	Tracer tests Hydrogeological modelling Tracer tests Analysis of key microbial and chemical contaminants controlled in protection zones

Hazardous event	**Cause**	**Risk**	**Control measure**	**Operational limits**		**Monitoring**			**Corrective action**	**Verification**
				Target	*Action required if*	*What?*	*When?*	*Who?*		
Backsiphonage from pipe into borehole	No back-flow preventer installed	Likely/ minor	Backflow preventer on mains	Backflow preventer installed	Lack of backflow preventer	Inspect pumping works	Installations Periodic checks	Constructor Operator	Backflow preventer installed	Audit of wellhead and pumping works
Failure in disinfection process	Disinfection process fails	Unlikely/ major to catastrophic	Effective chlorination with contact time	Ct value adequate and residual produced	Lack of residual	Monitoring chlorine dosing and residual	Daily/ hourly	Operator	Take pump off-line and repair disinfection unit	Audit of results *E. coli* Faecal streptococci Bacteriophages
Mobilisation of toxic chemicals and elution of viruses	Changes in land use and increased recharge through irrigation leads to mobilisation and elution	Rare/ minor to moderate	Land use control, in particular managing irrigation	Little artificial recharge through irrigation, pH and Eh of water stable	Significant changes in land use Increased use of irrigation	Land use pH of groundwater Redox (Eh)	Weekly	Operator	Reduce artificial recharge	*E. coli* Faecal streptococci Bacteriophages Chemicals of concern
Leaching of microbial contaminants into aquifer	Leaching of faecal material from sanitation, solid waste, drains	Moderate	Protection zones and set-back distances	Lateral separation defined on basis of travel times and hydrogeology	Latrines/sewers built or solid waste dumps within separation distance	Sanitary inspection: inspection of protection zone, electric conductivity, sewer leakage	Monthly	Operator	Remove pollutant sources Improve sanitation design Reduce sewer leakage Insert cut-off walls around sewers	Inspection *E. coli* Faecal streptococci Bacteriophages Nitrate Chloride Tracer tests

Hazardous event	**Cause**	**Risk**	**Control measure**	**Operational limits**		**Monitoring**			**Corrective action**	**Verification**
				Target	*Action required if*	*What?*	*When?*	*Who?*		
Groundwater contains naturally occurring chemicals	Geological setting means chemicals present at toxic levels	Moderate	Source selection	Use of groundwater with no natural chemical at harmful levels	Evidence of natural contaminants	Risk assessment of geological setting Initial assessment of water quality	Before installation	Constructor	Use alternative source Treatment	Risk assessment Water quality assessment Monitoring of chemicals of concern
Agricultural pollution: nitrate	Use of inorganic or organic fertilizers stock density	Unlikely/ minor	Protection zone	Nitrate vulnerable zones defined for aquifer prevent excessive leaching	Evidence of increasing nitrate levels	Monitor nitrate in groundwater Monitor fertilizer applications Monitor stock densities	Monthly	Supplier Environment Agency	Control of fertilizer applications Blending of drinking-water	Nitrate levels in ground-water Audit fertilizer applications Audit stick densities
Agricultural pollution: pesticides	Pesticides leached into the groundwater	Unlikely/ minor	Protection zone	Pesticide applications controlled in recharge area	Evidence of increasing pesticides in water Evidence of pesticide application at high-risk locations and times	Monitor pesticide applications	Monthly	Supplier Environment Agency	Control of pesticide applications	Pesticide levels in ground-water Audit pesticide applications
Pollution from urban areas contaminates groundwater	Poorly sealed drains cause recharge of ground-water	Moderate/ minor	Protection zones	Drainage water unable to recharge groundwater	Poorly constructed drains increase potential for recharge	Inspection	Weekly	Operator	Ensure all drains properly sealed in recharge or vulnerable areas	Audit drainage channel design, construction and maintenance

Hazardous event	**Cause**	**Risk**	**Control measure**	**Operational limits**		**Monitoring**			**Corrective action**	**Verification**
				Target	*Action required if*	*What?*	*When?*	*Who?*		
Leaching of chemicals from landfill sites into ground-water	Leaching of chemicals from landfills, waste dumps, industrial discharges to ground	Moderate/ minor	Protection zone	Landfills are sanitary and properly sealed Landfill presence controlled on basis of travel times and hydrogeology	Monitoring around pollutant sources indicate increasing pollution migration	Monitor for key contaminants around pollutant sources Monitor bills of lading	Weekly/daily	Waste managers Environment Agency Supplier	Move pollutant sources Improve pollution containment Monitor network around pollutant sources	Inspection Analysis of chemical composition of pollution Analysis of water quality Audit bills of lading for composition of waste
Pathogens from hospital wastes contaminate ground-water	Poor disposal of hospital wastes allows direct ingress of leaching into ground-water	Unlikely/ catastrophic	Proper hospital waste disposal	Hospital wastes with pathogenic material incinerated	Hospital waste disposal in dumps or ground containers	Monitor hospital waste disposal methods	Daily	Water supplier Health authorities	Ensure all pathogenic material incinerated or sterilized	Audit hospital waste disposal
Industrial discharges contaminated ground-water	Poorly disposed of industrial waste can inundate groundwater source or leach into aquifer	Moderate/ minor	Waste containment and treatment	Effective disposal methods prevent spills and leaching	Waste disposal methods do not provide security against inundation and leaching	Monitor containment methods at industrial sites	Monthly	Supplier Environment Agency	Ensure all industrial waste is properly contained and treated at the site	Audit industrial wastewater treatment plants

Table 16.6. 'Model' Water Safety Plan for boreholes fitted with handpumps (based on Davison *et al.*, 2005)

Hazardous event	**Cause**	**Risk**	**Control measure**	**Operational limits**		**Monitoring**			**Corrective action**	**Verification**
				Target	*Action*	*What?*	*When?*	*Who?*		
Ingress of contaminated surface water directly into borehole	Poor wellhead completion	Unlikely/ major	Proper wellhead completion measures	1 m concrete apron around wellhead Lining extends 30 cm above the apron Drainage ditches in place	Lining stops at ground level Apron damaged or cracked Ditches full, faulty or absent	Sanitary inspection	Monthly	Community operator	Extend lining Repair apron Clean and repair drainage ditches	Sanitary inspection *E. coli* Faecal streptococci Bacteriophages
Ingress of contaminants due to poor construction or damage to the lining	Poorly maintained wellhead completion	Moderate/ major	Proper wellhead completion	Top 5 m of the annulus sealed Rising main in good condition	Annulus sealed for less than 3 m Colour changes Increased pumping required to raise water	Sanitary inspection Water clarity	Annual/as need arises	Community operator	Insert seal around annulus Replace worn and corroded rising mains Use materials less likely to corrode (e.g. plastics)	Sanitary inspection Analysis of colour and iron
Borehole area is inundated with contaminated surface water	Lack of diversion ditches	Unlikely/ major	Good drainage around wellhead	Diversion ditches of adequate size, in good condition and clear of rubbish	Ditch has rubbish or shows signs of wear	Sanitary inspection	Monthly	Community operator	Repair and clean ditch Increase size of ditch using	Sanitary inspection
Contamination introduced as handpump requires priming	Priming water contaminated	Almost certain/ minor	Use direct handpump or clean water for priming	Water for priming stored in secure container	Priming water comes from contaminated source or is stored poorly	Inspection	Weekly	Community operator	Select handpump that does not require pumping	Test priming and borehole water for *E. coli* and faecal streptococci

Hazardous event	**Cause**	**Risk**	**Control measure**	**Operational limits**		**Monitoring**			**Corrective action**	**Verification**
				Target	*Action*	*What?*	*When?*	*Who?*		
Contaminated shallow water drawn into aquifer	Hydraulic connection exists between shallow and deeper aquifers allowing draw-down into deeper aquifer	Almost certain/ minor	Pumping regimes do not induce leaching	No evidence of drawdown of shallow groundwater	Evidence of shallow water drawdown (e.g. shallow wells start to dry up)	Colour Taste Odour Inspection	Annual/as need arises	Community operator	Set intake deeper (microbes) Water treatment (microbial) blending (chemicals)	*E. coli* Faecal streptococci Bacteriophages Nitrate Tracer studies Hydrological models Electric conductivity Redox potential
Leaching of microbial contaminants into aquifer	Leaching of faecal material from sanitation, solid waste, drains	Moderate	Provide adequate set-back distances defined on travel time	No sources of faecal material within set-back distance	Latrines/sewers built or solid waste dumps within separation distance	Inspection by community	Monthly	Community operator	Move pollutant sources Improve sanitation design Reduce sewer leakage	Inspection *E. coli* Faecal streptococci Bacteriophages Nitrate Chloride Tracer studies

Hazardous event	**Cause**	**Risk**	**Control measure**	**Operational limits**		**Monitoring**			**Corrective action**	**Verification**
				Target	*Action*	*What?*	*When?*	*Who?*		
Groundwater contains naturally occurring chemicals	Geological setting means chemicals present at toxic levels	Moderate	Select ground-water with acceptable levels of natural chemicals	Water quality assessments indicate water quality is acceptable	Evidence of natural contaminants	Risk assessment of geological setting Water quality assessment	Before construction Periodic evaluation	Water development agency	Use alternative source Treatment of water	Risk assessment Water quality assessment Monitoring of chemicals of concern
Leaching of chemicals into groundwater	Leaching of chemicals from landfills, waste dumps, discharges to ground	Moderate/ minor	Provide adequate set-back distances defined on travel time	No sources of chemicals within set-back distance	Pollutant discharges within set-back distance	Inspection by community	Monthly	Community operator	Move pollutant sources Improve pollution containment	Inspection Analysis of chemical composition of pollution Analysis of water quality

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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.

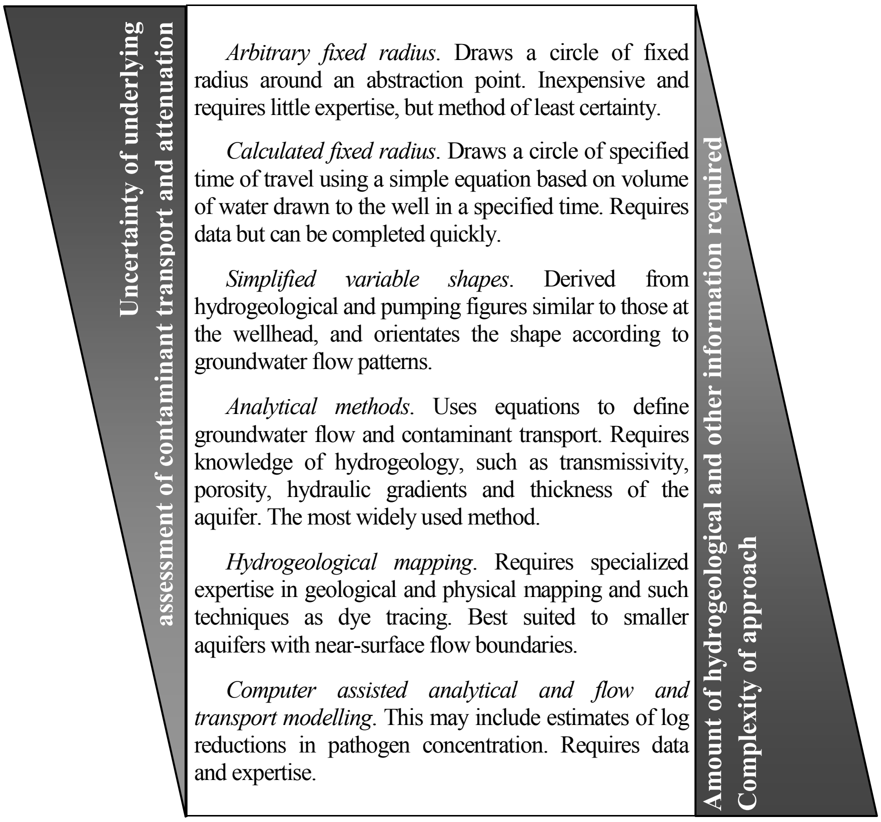
The number of zones defined to cover these function varies between countries, usually from 2-4. By placing some form of regulatory control on activities taking place on land which overlies vulnerable aquifers, their impact on the quality (and in some cases quantity) of the abstracted water can be minimized. 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 subsurface 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.



Arbitrary fixed radius. Draws a circle of fixed radius around an abstraction point. Inexpensive and requires little expertise, but method of least certainty.

Calculated fixed radius. Draws a circle of specified time of travel using a simple equation based on volume of water drawn to the well in a specified time. Requires data but can be completed quickly.

Simplified variable shapes. Derived from hydrogeological and pumping figures similar to those at the wellhead, and orientates the shape according to groundwater flow patterns.

Analytical methods. Uses equations to define groundwater flow and contaminant transport. Requires knowledge of hydrogeology, such as transmissivity, porosity, hydraulic gradients and thickness of the aquifer. The most widely used method.

Hydrogeological mapping. Requires specialized expertise in geological and physical mapping and such techniques as dye tracing. Best suited to smaller aquifers with near-surface flow boundaries.

Computer assisted analytical and flow and transport modelling. This may include estimates of log reductions in pathogen concentration. Requires data and expertise.

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 groundwater-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 persistence 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)

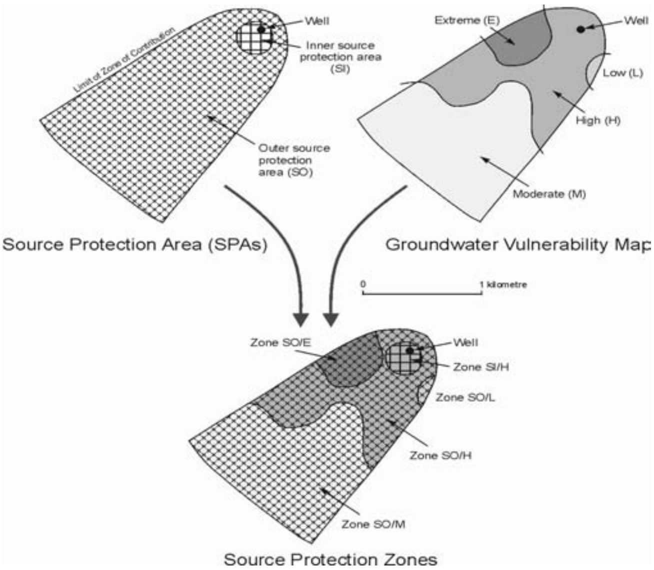


Figure 17.2. Delineation of source protection zones around a public supply well from the integration of the SPA map and the vulnerability map (DoELG, 1999)

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 ($1\ \text{m}^3/\text{h}$)	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.

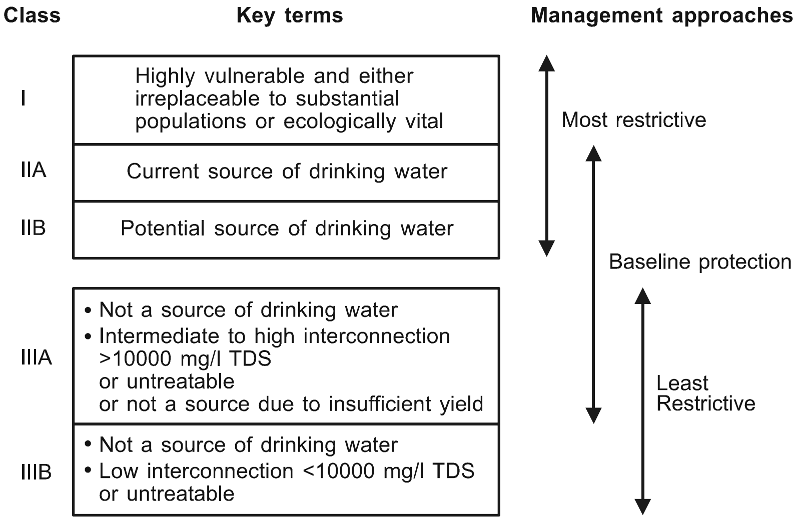


Figure 17.3. US EPA classification scheme (US EPA, 1986)

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 *Fish ponds*: microbial and chemical contamination due to short-circuits between ponds and groundwater *Private drinking-water wells*: direct ingress of microbial contamination due to unsanitary construction of wells or unsanitary practices *Solid waste disposal at the Sumberawan Temple*: leaching of chemicals into groundwater	All activities that directly impact on water quality, such as bathing and washing in ponds and streams Any use of fertilizers and manures All activities that impact on water quality in ponds, i.e. solid and/or liquid waste disposal Any disposal of solid waste at the Sumberawan Temple site	Repairing of the fence that protects the spring box	3	1	4	Priority I
			Implementation of a training programme on best farming practices with regard to the use of fertilizers	3	3	6	Priority I
			Inspection and surveillance of farming practices	3	3	6	Priority I
			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 *Deforestation*: devastation of the recharge area	Use of manure and chemical fertilizers in excess application rates, i.e. in contradiction to best farming practices Felling forest Change of land use	Implementation of a training programme on best farming practices with regard to the usage of fertilizers and pesticides	2	3	5	Priority II
			Promotion of usage of environment friendly pesticides	2	2	4	Priority III
			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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18

Sanitary completion of protection works around groundwater sources

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The proper sanitary completion of groundwater sources is of particular relevance to the microbial quality of water. It is essential to prevent the direct contamination of groundwater at the point of abstraction or resulting from rapid recharge pathways close to the source. Where contamination is allowed to directly enter the groundwater source or reach groundwater close to the point of abstraction, the travel time may be too limited to ensure adequate die-off and the processes of attenuation may not be effective in reducing the numbers of pathogens (Robertson and Edberg, 1997).

Sanitary completion is also important in preventing direct chemical contamination, but often does not provide the same degree of protection. The subsurface leaching and transport of mobile and persistent chemical contaminants means that land use controls will be required to limit risks. This is illustrated, for instance, by studies in a small town in Uganda that showed little contamination by microbial contaminants, but significant increases in nitrate derived from faecal sources (Barrett *et al.*, 2000a). Large-scale protection measures, such as designation of groundwater protection zones, are discussed in Chapter 17.

Sanitary completion refers to the protection works at the abstraction point and the immediate surrounding areas. It is sometimes also referred to as wellhead protection, although this would usually cover a wider area around the well than covered in this

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chapter. In this chapter, sanitary completion includes the underground and above ground construction of the abstraction facility as well as the immediate area surrounding the abstraction point.

NOTE ▶ *This chapter introduces options for controlling risks through sanitary completion. The information presented supports defining control measures in the development of a Water Safety Plan (Chapter 16).*

18.1 SANITARY COMPLETION AND HEALTH

The direct contamination of groundwater sources resulting from poor sanitary completion has been linked to both endemic disease and outbreaks. Such contamination is present in both developed and developing countries. For instance, Olson *et al.* (2002) describe an outbreak of *E.coli* O157:H7 in Alpine, Wyoming, including cases of haemolytic uraemic syndrome, which was related to consumption of water from a poorly protected spring which sanitary surveys had identified as being at risk from contamination by surface water. Poor sanitary completion measures also appear to have played a role in the Walkerton outbreak in Canada (O'Connor, 2002). In developing countries, the use of poorly protected groundwater sources has been linked to acute diarrhoeal disease (Trivedi *et al.,* 1971; Nasinyama *et al.*, 2000). Good sanitary completion measures have been shown to be necessary to maintain the quality of water and protect public health (US EPA, 1993; Pedley and Howard, 1997; Robertson and Edberg, 1997).

The effectiveness of sanitary completion in reducing risks of pathogens is profound as it provides a barrier to direct contamination of the source (Robertson and Edberg, 1997). The degree to which risks will be reduced, however, varies between pathogen types and aquifer types and there is a need for multiple interventions to act as barriers to most pathogen types.

For many aquifers, good sanitary completion measures will control the majority of risks posed by protozoa. Sanitary completion will greatly reduce the risks from bacteria in alluvial aquifers, but significant risks will remain in fracture flow aquifers where the enforcement of protection zones and, possibly, disinfection will be required. Sanitary completion measures will in general provide much less protection against risks posed by viruses, with protection zones and disinfection being required to reduce risks.

Most sanitary completion measures do not significantly add costs onto good standard design practice. There are cost implications, however, in ensuring that effective maintenance is performed to prevent basic protection measures from deteriorating and becoming ineffective. In some cases, cost considerations may be important with regard to selecting whether improvement of sanitary completion measures or alternative interventions will be the preferred option. For instance, where an aquifer is subjected to low-level or intermittent microbial contamination, it may be more cost effective to chlorinate the water prior to distribution than to try to deepen the borehole.

18.2 THE NEEDS FOR EFFECTIVE CONTROL MEASURES IN SANITARY COMPLETION

Sanitary completion typically includes a number of essential control measures to prevent the contamination of groundwater. Failures in such control measures have been reported from a variety of situations in both developed and developing countries (Lewis and Chilton, 1984; Lloyd and Helmer, 1991; Platenberg and Zaki, 1993; Daly and Woods, 1995; Gelinas *et al.*, 1996; Howard *et al.,* 2003). In addition to the immediate protection works at the abstraction point, the appropriate sealing of abandoned wells is also noted as essential to protect functioning groundwater sources (Rojas *et al.,* 1995; Robertson and Edberg, 1997).

Failures in sanitary completion measures may result from poor construction and in particular lack of adherence to basic quality standards. For example poor jointing on casings of boreholes, incorrect selection and placement of grouting, poor selection and installation of gravel packs, poorly mixed concrete used for linings and aprons may all result in seepage of contaminated water into groundwater sources (Howsam, 1990; US EPA, 1993).

Some drilling techniques lead to increased risks because they do not allow for grouting around the casing to be used (ARGOSS, 2001). Failure to consider the pH of the groundwater may lead to corrosion and rapid deterioration of rising mains, resulting in loss of water and abandonment of the supply (Leake and Kamal, 1990). In addition, methods of water lifting can present a direct route of contamination such as through the priming of handpumps with contaminated water (MacDonald *et al.,*1999).

Failures in sanitary completion may also result from poor maintenance (Lloyd and Bartram, 1991; Lloyd and Helmer, 1991; Platenberg and Zaki, 1993; US EPA, 1993; Daly and Woods, 1995; Howard *et al*., 2003). In many cases specific measures constructed to protect a groundwater source fail because other measures, such as fences and diversion ditches, have not been maintained. The failure to maintain ditches and fences can result in increased access to the groundwater source, increased stress and erosion on the other protection measures and increased likelihood of inundation by surface water.

Control measures as part of sanitary completion should be identified and implemented in the planning, design, construction, operation and maintenance of an abstraction facility. As the risks to groundwater sources can be described using the source-pathway-receptor model (see Table 8.8 in Chapter 8.5.2), control measures can be categorised as: controlling the source of hazards, e.g. faecal material from a pit latrine overlying an aquifer and close to an abstraction point, and controlling pathways to avoid direct or very rapid ingress of contaminated water, e.g. through cracks in the casing of boreholes, improperly sealed apron surrounding the headwall of a dug well or borehole, eroded backfilled area of a protected spring, abandoned dug wells and borrow pits.

Control measures both for sources and for pathways include indirect measures to decrease the likelihood of a hazard or pathway developing, such as a fence around the water source to prevent access of animals or humans which could be a source of hazard (through defecation) or cause a pathway (through causing damage to the source or the immediate surrounding area).

In many cases, a combination of control measures addressing hazard sources and contamination pathways is necessary. Sanitary completion provides one barrier to contamination from such sources, but should be integrated with proper pollution containment practices and other environment engineering interventions (such as improved drainage) to be effective.

18.3 CONTROL MEASURES IN SANITARY COMPLETION: PLANNING AND DESIGN

The initial design of a groundwater abstraction facility is crucial in determining how protected the source will be. Some background information and a number of basic considerations should be taken into account at this stage.

Planning site and design in relation to the hydrogeological environment

The first step in sanitary completion is to understand the nature of the hydrogeological environment – where and how many aquifers exist, what type of aquifers exist, expected yields, depth and nature of the overburden and the degree of interconnection between different aquifers (Chapter 8). It is also important to assess how the water will be abstracted – are there springs or must the groundwater be abstracted through sinking a well or borehole into the ground? This information can then be used to make basic decisions such as the type of technology to be used, the depth of abstraction and additional protection measures required.

Where aquifers are deep or multiple aquifers are found, setting the intake deeper is likely to improve the microbial quality of water. In many aquifers, in particular relatively fine-grained aquifers, there is far less vertical movement of water (and therefore pathogens) than horizontal movement. The increase in travel times for relatively small increases in depth may be many tens or hundreds of days (ARGOSS, 2001). This increases the potential for die-off of pathogens and potentially greater dispersion; although in the latter case sophisticated models may be required to predict this. It may also increase the potential for attenuation, although this cannot be relied upon.

Sinking tubewells into deeper (usually older) aquifers may also be an important way of avoiding chemical contamination in shallow groundwater, as is the case in relation to arsenic contamination in Bangladesh (Ahmed *et al*., 2002). Where tubewells are deepened it is important that shallower layers are cased off to prevent ingress. Often the incremental cost of deepening a well is relatively low in comparison to the overall capital investment and thus yields a significant cost-benefit. Deepening tubewells requires ascertaining whether there is no or very limited hydraulic connection between contaminated shallow and uncontaminated deeper aquifers. Hydraulic connection between aquifers is relatively common in aquifers found in weathered basement rocks and may also occur in alluvial aquifer sequences with no defined aquitard or aquiclude. Where hydraulic connections exist, deepening a tubewell may limit the improvement of water quality, as induced leakage from shallow aquifers may still lead to contamination.

Planning control measures in designing abstraction may be hampered by lack of hydrogeological information. For example in fracture aquifers it may be difficult to determine the level of risk posed to a deep aquifer by a contaminated shallow aquifer. Geophysical investigation and detailed assessment may provide some, but possibly not all, the answers required during the design stage. In such cases, monitoring as part of validation of the design chosen is particularly important.

Planning site, design and operational control measures in relation to the outcome of hazard assessment

As discussed in Section II and Chapter 14 of this book, a critical step before embarking on the design of a groundwater source is to evaluate what hazards exist close to the proposed site and their potential to be attenuated or diluted. This includes determining whether particular aquifers are contaminated and therefore whether their use as a drinking-water supply is justified.

Where the situation assessment identifies existing contamination of a well or spring, or a high potential for pollution from activities and conditions too close to the abstraction facility, control measures can either be identified towards removing the cause of the hazard(s) (see also Section V), or towards changing the site or depth of the well. While removing hazards would be the preferable, in practice population density and/or severity of contamination may make relocation of wells more feasible.

Whilst an emphasis should be placed on ensuring microbial quality of water, attention should be paid to the chemical quality of different groundwaters. Assessing whether particular aquifers contain toxic levels of chemicals (e.g. arsenic) or whether the levels of chemicals will affect the acceptability of water to consumers (e.g. high iron or manganese levels) or cause unacceptable operational problems (e.g. very hard waters) is critical in the design process. The acceptability of water is a particular problem as this may lead households to reject the use of an otherwise safe source and use contaminated sources for drinking. This not only fails to meet basic health needs for low-risk drinking-water, but also represents a significant waste of resources.

In cases where the hazard only represents a risk under certain pumping conditions, the pumping regime could be defined as control measure in order to reduce the influence of the hazard. This is unlikely to be satisfactory, however, as there may be considerable uncertainty both in the abstraction model used as basis for decisions, and in operational monitoring and corrective action to ascertain that this pumping regime is always adhered to.

If the hazard cannot be removed and changes in design of the source are not possible, post-abstraction disinfection is likely to be an effective control measure. In some cases, it will be more effective to use a lower microbial quality of water and then apply treatment at household or community level and/or implement a health education programme dealing with steps available at the household level to reduce the risks. Also, a residual risk may have to be retained if contamination is relatively low, other routes of disease transmission are more significant than water and are therefore other interventions are a greater public health priority where resources are insufficient to simultaneously improve drinking-water quality.

18.3.1 Drainage and fencing

Control measures are important to protect abstraction facilities against the potential for inundation by contaminated surface water or damage by animals or overland flows caused by heavy rainfall by diverting surface water away from the headworks. For protected springs this diversion should be located above the protection works and should direct the water into a drainage ditch downstream and away from the spring. For dug wells and boreholes, diversion ditches should circle the headworks and drain the water away from the source. In designing the ditch, the topography and likely overland flows should be evaluated to ensure that the depth of the ditch is adequate to remove all stormwater.

Diversion ditches should be located some way from the groundwater source, but not so far that significant overland flow will be generated within the area between the ditch and the headworks. A general rule of thumb is a minimum of 6 m and preferably 10 m for boreholes and dug wells and up to 20 m for protected springs (Morgan, 1990).

Restricting access by both humans and animals to the headworks is also important to reduce risks of contamination and thus, where possible, water sources should be enclosed by a fence. However, this needs to be balanced against cultural norms, for instance fencing of community water sources in Bangladesh is often not practiced because this may be interpreted as restricting the use of the source.

The wellhead of boreholes serving a piped distribution system should be located within a locked building which only the operation staff of the water supplier should have access to. Where users must collect water directly at the borehole or dug well source, fencing is still required and access should be restricted to only one or two entrances. For springs, the whole backfilled area should be fenced and inaccessible as users will collect water from outlets on the spring box. Where the spring feeds a gravity piped water system, the whole spring protection works should be fenced off and access limited to the community operator. All valve and junctions boxes should have concrete lined sides and a lockable lid.

18.3.2 Design of boreholes

Boreholes or tubewells may be shallow (5-45 m) or deep (up to several hundred metres). The choice of pump (hand, mechanized or electric submersible) to withdraw the water will depend on the hydraulic (or pumping) head in the pump, with handpumps being typically constrained to depths of 45 m or less. Where confined or semi-confined aquifers are used, the water table may rise considerably higher than the depth of the well and a handpump may still be used despite the well being physically relatively deep. Where mechanized or electric submersible pumps are used, they are typically linked to a distribution system. An example of a shallow borehole is shown in Figure 18.1. Selection of appropriate design such as the use of geotextile stockings, telescopic screen or external gravel packs can improve filtration and reduce potential sanitary risk (Driscoll, 1986).

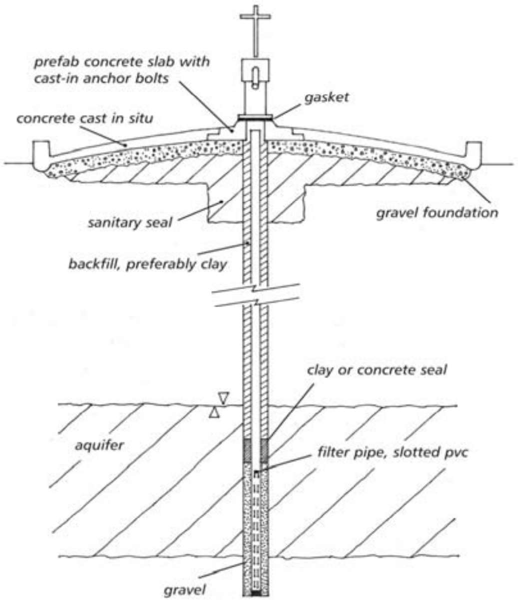

Figure 18.1. Design of a shallow borehole with handpump

For all boreholes or tubewells ensuring proper sanitary completion of the above ground infrastructure is essential to prevent direct ingress of contaminated surface water. Key components are to provide a casing over the unsaturated zone and over the upper part of the aquifer which may be expected to dewater during pumping. It is important to provide a bentonite grout seal for at least the top 1-3 m, which should be continuous with a concrete apron surrounding the top of the borehole (Driscoll, 1986). The apron must be in good condition with cracks and faults repaired rapidly.

Sanitary completion of tubewells/boreholes will be dependent on the method of drilling. For instance, MacDonald *et al.* (1999) note that the use of the sludger method commonly employed in the alluvial aquifers in Bangladesh increases susceptibility to contamination via routes close to the tubewell because it precludes sealing the annulus between the casing and drilled tubewell. However, as the formation typically collapses around the casing, the susceptibility can be reduced (Ahmed *et al.*, 2002).

Boreholes are usually fully developed prior to commissioning to ensure adequate flow using a variety of techniques. Well development is not typically designed to improve water quality, but care is needed when using some techniques (notably hydrofracturing and acidization) to avoid the creation of preferential flow paths in consolidated formations that could allow rapid transport of contaminants.

18.3.3 Design of dug wells

Most hand-dug wells are shallow (typically 20 m or less in depth) although wells as deep as 120 m have been constructed (Watt and Wood, 1977). They are often more vulnerable to contamination than boreholes, thus while some shallow dug wells have mechanized pumping, the majority (particularly those in developing countries) have water abstraction through some form of handpump, windlass or rope and bucket system. A typical design is shown in Figure 18.2.

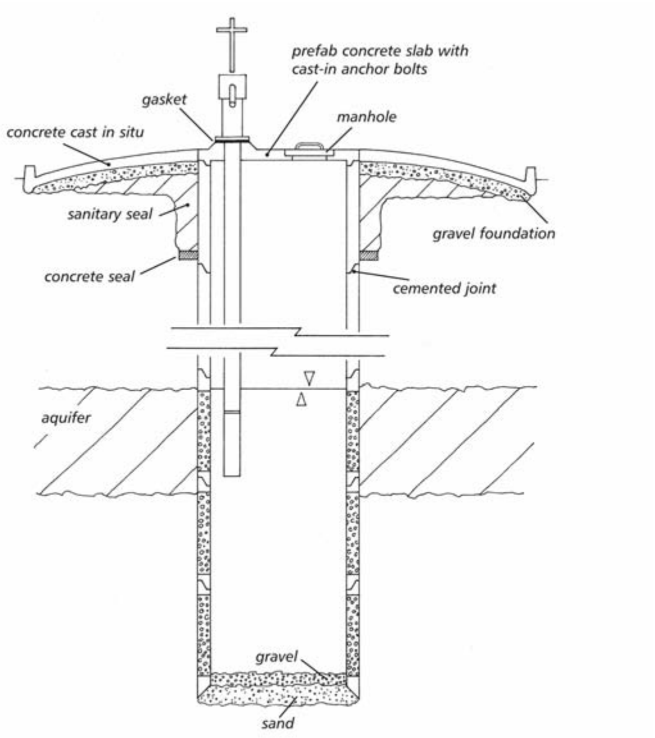

Figure 18.2. Design of a dug well with handpump

Hand-dug well designs usually have some form of lining over the unsaturated zone. In order to secure a year-round supply, caissons may be sunk below the water table to prevent drying. The design should include an apron surrounding the top of the well (usually of 1-3 m radius) with lining extended 30-50 cm above the top of the apron to provide protection against direct ingress of surface water. It is preferable that a cover is put on the well to prevent direct contamination of the water (Collins, 2000).

Studies by Lewis and Chilton (1984) note that the design, construction, operation and maintenance of the apron results in a direct reduction in levels of contamination. Dug wells can be backfilled with a sanitary seal of between 1-3 m, which increases travel time resulting in increased die off rates of pathogens. However, backfilling of wells is difficult if deepening of the well is required during drought periods. Alternative techniques such as curbing (attachment of section stabilizers) can be used to prevent movement of the shaft section of well and therefore not disturb the sanitary seal (Watt and Wood, 1977).

The means of abstraction should minimize the potential for introducing contamination from dirty containers. This may include using a handpump or other sanitary means of withdrawing water from the well such as a rope and washer pump, which have been shown to be effective in reducing levels of contamination (Gorter *et al*., 1995). (See Section 18.5.1 for more detail about risks associated with pumps.) Where a windlass, rope and pulley system with a bucket is used, then only one bucket should enter the well and hygiene education should emphasize the need to keep the well bucket from coming into contact with the ground.

Hand dug wells often represent particular problems for sustaining good quality water, as it is difficult to ensure that very shallow water cannot enter the lining during wet periods. There are a number of different linings that may be used, including precast concrete, concrete cast in-situ and brick linings (Collins, 2000). Each of these methods gives varying degrees of sanitary protection.

Where water quality is difficult to maintain, additional improvements have been made to dug wells. These include the addition of a small sand filter set inside a box at the base of the well, a permeable base plate or ongoing chlorination of the water in the well (Lloyd and Helmer, 1991; WHO, 1997; Godfrey *et al.*, 2003). Chlorination has proven to be effective in post-emergency situations where other technology alternatives are unavailable but its effectiveness in terms of sustainability is questionable (Rowe *et al*., 1998; Godfrey, 2003).

18.3.4 Design of protected springs

A spring is a natural groundwater source which is protected by providing a concrete headwall or spring box around the eye of the spring (where water emerges) that prevents direct contamination (WHO, 1997; Howard *et al.*, 2001; Meuli and Wehrle, 2001). There are a number of designs for protected springs, all of which utilize some form of retaining wall or spring box with an excavated area backfilled with loose material to encourage spring flow towards the outlet. A protective cover usually overlies the excavated area and the area is fenced for some distance to prevent direct access by humans and animals. One design that has been used in periurban areas is shown in Figure 18.3.

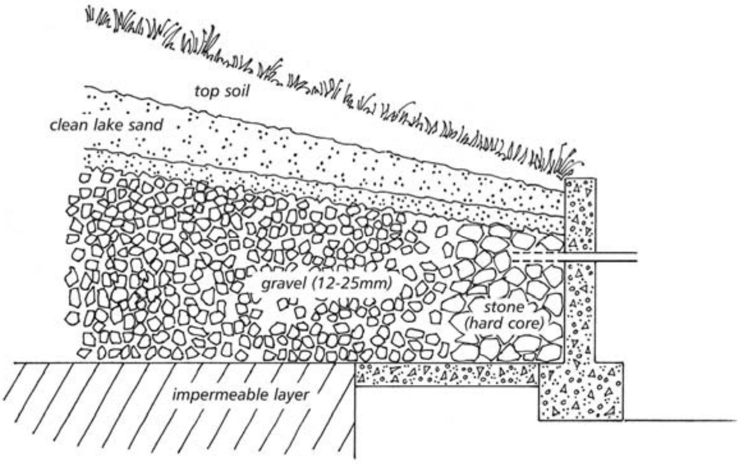

Figure 18.3. Cross-section of the backfill of a protected spring (Howard *et al.,* 2001)

Where protection is poor, contamination may occur at the point of emergence due to recharge by contaminated water in the immediate area. Thus the proper protection of the spring eye becomes vital. At most springs, the eye of the spring is excavated and the area backfilled with loose material. The filter media should be sufficiently fine to provide reasonable filtration of the groundwater entering from the spring eye and any surface water percolating through the immediate area: usually gravel although finer media may be required in more polluted areas.

It is important that this filter is overlain by an impermeable layer, commonly clay but can be a concrete cover, to reduce direct infiltration of surface water, and the whole area grassed (Howard *et al.,* 2001; Meuli and Wehrle, 2001). The filter media should be placed in the backfill area from the base of the excavation up to the expected highest level of wet season water table rise (only applicable in gravity springs).

18.3.5 Design of infiltration galleries

Infiltration galleries come in a variety of forms – they may run alongside rivers or other surface water bodies or may tap a spring line. They can be used as a part of a treatment train or may provide water directly via a shallow well or from a gravity-fed piped water supply. Infiltration galleries have been used in many countries and often have long life spans, for instance an infiltration gallery has been in operation in Lima, Peru for over 100 years and still provides high quality water with limited maintenance (Rojas *et al.*, 1995).

When using an infiltration gallery it is important to ensure that the collector pipe is laid at an adequate depth to ensure a year-round supply. The collector pipe should be surrounded by a gravel pack designed to reduce the velocity of water entering the drain to ensure that suspended sediments are removed. It is preferable that the intake holes be on the underside of the collector pipe to increase the flow path length. However, it is recognized that in most cases inlet holes will be required on the full pipe for hydraulic reasons and that the gravel pack must be laid properly. The interior of infiltration galleries will be self-cleaning if the velocity is at least 1 m per second.

18.4 CONTROL MEASURES IN SANITARY COMPLETION: CONSTRUCTION AND MATERIALS

The construction process and materials used are critical in ensuring that proper sanitary completion is achieved. Substandard work should be rejected. Poor construction quality allows faults to develop at the abstraction point. It is essential that technicians undertaking water source construction are properly trained and that guidelines for construction (for instance concrete mixes, rising main materials, etc.) are provided and followed.

The materials used can be critical to prevent water quality deterioration. Cement should be of good quality and within the recommended date of use. Sand and gravel should be clean and mixed in the proportions specified in the design. Reinforcing materials should be free of rust and dirt to ensure that a firm bond is formed with the concrete and care should be taken in selecting the gauge of reinforcing materials.

An important part of the construction process is quality control. This requires periodic checking and auditing of field practices to ensure that they are consistent with stated quality goals and objectives that the construction agency has set itself. Such quality control is necessary in all situations, whether construction is undertaken by the public or private sector. In all cases, but particularly where work is contracted to a third party, it is essential that there is evidence that the quality of construction is adequate. This may take the form of inspection and signing off a contract prior to full payment, or unannounced site visits.

18.4.1 Pumps and rising mains

For dug wells and tubewells, the selection of the rising main material is important. Galvanized iron rising mains should be avoided where water is relatively acid water because they are likely to corrode and lead to abandonment of the use of the handpump or the source. Where suction pumps are used, it is important that pumps are selected which have a non-return foot valve and do not require priming water to be added. As priming water is often taken from surface water or other stored household water, it may be contaminated (ARGOSS, 2001). Where priming water must be used, then it is important that only water collected from the well and stored in a covered container is used.

18.4.2 Cleaning of facilities prior to commissioning

For boreholes and dug-wells, good hygiene should be practiced by the team during construction. However, as some contamination will almost always remain, the wells should be thoroughly cleaned and disinfected prior to use and after maintenance tasks within the well.

For dug wells, the lining and caisson walls should be scrubbed with a chlorine solution prior to commissioning; after this washing down with chlorinated water should be sufficient. Where a handpump is installed on a dug well, the rising main should be filled with a chlorine solution and left to stand for at least one hour and preferably overnight.

Disinfection of boreholes requires filling the casing with a chlorine solution and leaving it to stand for at least one hour and preferably overnight. In both cases, the chlorinated water should be pumped to waste before use.

18.5 CONTROL MEASURES IN SANITARY COMPLETION: OPERATION AND MAINTENANCE

Whilst good design and construction will do much to ensure that wellhead protection is adequate, ensuring that it remains in good condition through ongoing preventative maintenance and repair is essential. This applies equally to springs and wells of large utilities and to small community or household supplies. The inspection routine should be defined in a management plan and include the recording of any deterioration detected and the action to be taken by whom and when.

For example, where pumps are used (whether handpump or mechanized), a stock of tools and spares should be kept by the operator so that repairs can be carried out quickly. Inherent to this is developing an effective supply chain for spares. In South Asia this has been successful as the small-scale private sector has been able to meet demand. In Africa, developing adequate supply chains has been more problematic, leading to relatively large numbers of boreholes being non-functional. In more developed countries, operators would normally have a store of the requisite tools and spares or would be able to source these quickly.

Proper training of operators of a supply is of critical importance for them to have and have the skills and knowledge to undertake at least basic preventative maintenance and perform minor repairs. More than one operator per source should be trained to ensure that maintenance and repairs can still be undertaken even if an operator moves away from the area or cannot undertake work at a particular time. For utility supplies, a number of operators may be identified who work at the supply on a rotational basis. Operators should have access to guidance and information about maintenance and repairs – e.g. specifying frequencies for replacement or worn parts and giving detailed information of repair procedures.

Where possible, the operators of water supplies should receive ongoing support from technical or professional support staff. Very often, even limited support in terms of regular visits to a supply to undertake an inspection and to meet with the operators of the supply can be very effective in sustaining good operation. This is particularly important for sustaining good quality small water supplies in both developed and developing countries and in rural and urban areas (Bartram, 1999; Holden, 1999).

In addition to basic maintenance and repairs of equipment, it is important that basic cleaning tasks are routinely undertaken. This involves cleaning and repairing diversion ditches, ensuring that wastewater ditches from springs do not become blocked and allowed to flood the source and ensuring the fence remains in good condition. Such tasks are best defined in management plans and usually are not onerous if done regularly. They can make a crucial difference in water quality control. Such activities should be supported by inspections of the site by the operator.

Experience shows that in order to sustain operation and maintenance some form of contribution from the users for the upkeep of the water source is very effective. In rural areas of low-income countries this may involve the contribution of labour. Other communities, particularly those in wealthier countries and those in urban areas of developing countries, may rely on payment by the users for the water services supplied. Most communities are willing to pay for water services providing the charges are realistic and the service meets the demands of the users. Routine payment is often preferred, as systems that operate solely on the collection of fees once a breakdown has occurred will mean that faults take longer to repair, although the latter approach has been found to work in some communities, for example in Eastern Uganda.

In both cases, community organization is often key to ensuring that maintenance procedures are supported. This may take the form of a committee that oversees the operation of the water supply. In many low-income countries, such a committee may be specific to the water source and it is preferable to ensure that the members are representative of the different interest groups in the community and in particular that women's concerns are adequately addressed. In higher-income countries such a committee may be a subcommittee from a local council or government at the local level. For instance in Chile user committees have been set up for all water supplies constructed by the regional water supply company using subsidies from the Government. These committees are supported by training programmes provided by the regional water supply companies who provide training to managers and operators of the supplies.

18.6 ASSESSMENT OF SANITARY COMPLETION AND ESTABLISHING PRIORITY RISK FACTORS

The state of sanitary completion can be assessed using inspection methodologies, as described further below. These are particularly important in the context of system assessment to determine risks and priorities for upgrading abstraction facilities as well as for defining control measures in the context of developing a Water Safety Plan (WSP). Sanitary inspections may also be used in verification via a surveillance programme using standardised approaches (Howard, 2002; WHO, 1997). Examples of such forms are commonly available, for instance in Volume 3 of the *Guidelines for Drinking-water Quality* (1997). In both cases, water quality data would also typically be collected to allow combined analysis of the effectiveness of the control measures.

Sanitary inspection methods may also be used in the routine operational monitoring of the water source as part of a WSP. Sanitary inspection approaches for routine monitoring in developed countries are likely to be the same as those used in assessment. In developing countries, other tools such as simple pictorial monitoring tools may be more effective. Routine monitoring may include some analysis of basic water quality parameters, particularly if chlorination is practiced, but this is dependent on the skill of the operators and funds for supporting such analysis.

18.6.1 Sanitary inspection

Sanitary inspection provides an easy but effective means of both assessing and monitoring sanitary completion, particularly when this employs a standardized and quantifiable approach (Lloyd and Bartram, 1991; Lloyd and Helmer, 1991; WHO, 1997). Unless a standardized approach is adopted, problems are commonly found in comparing the findings between different inspectors (WHO, 1997; Howard, 2002). This leads to inaccurate and unreliable results and limits the potential for subsequent analysis of the data. A quantified approach allows an overall risk score to be calculated in order to assess the state of supply systems and to identify priorities for action. It also permits comparisons between different source types once the data is converted into a percentage risk.

Sanitary inspections should be undertaken frequently, at least as often as samples are analysed for verifying water quality and in some cases more often. Risks are not static, they change over time as new development occurs in the area and are sometimes due to poor maintenance practices. Certain risks may also be important only seasonally, for instance the collection of surface water uphill of a groundwater source may only occur during wet periods. Therefore inspections may be required in both wet and dry seasons.

Most sanitary inspections involve a series of simple questions with Yes/No answers. As the questions are usually framed in such a way that a positive answer indicates the presence of a risk, typically a score is allocated for a positive answer and no score for a negative answer. Adding up the positive answers provides an overall sanitary risk score. An example of a sanitary inspection form is given in Box 18.1 below. Other examples are available from volume 3 of the *Guidelines for Drinking-water Quality* (WHO, 1997).

In the form in Box 18.1, questions 7, 8 and 10 refer to potential sources of faeces in the environment; questions 1, 2 and 3 refer to direct pathway factors; and, questions 4, 5, 6 and 9 refer to indirect factors. The analysis of these factors in relation to water quality provides useful information regarding which remedial and preventative actions are required for the specific water source. Data collected this way can further be aggregated and evaluated across a range of abstraction facilities of a given region in order to identify key risk factors.

Box 18.1. Example of a sanitary inspection form (based on Howard, 2002)

I. Type of Facility: PROTECTED SPRING

1. General Information: Division: Parish:
2. Code Number:
3. Date of Visit:
4. Water sample taken? Sample No.:
   Faecal Coliform/100 ml:

II. Specific Diagnostic Information for Assessment

		Risk
1.	Is the spring unprotected?	Y/N
2.	Is the masonry protecting the spring faulty?	Y/N
3.	Is the backfill area behind the retaining wall eroded?	Y/N
4.	Does spilt water flood the collection area?	Y/N
5.	Is the fence absent or faulty?	Y/N
6.	Can animals have access within 10 m of the spring?	Y/N
7.	Is there a latrine uphill and/or within 30 m of the spring?	Y/N
8.	Does surface water collect uphill of the spring?	Y/N
9.	Is the diversion ditch above the spring absent or non-functional?	Y/N
10.	Are there any other sources of pollution uphill of the spring (e.g. solid waste)?	Y/N

Total Score of Risks: /10 (Risk score 0-3=low; 3-5=medium; 6-8=high; 9-10=very high)

III. Results and Recommendations

The following important points of risk were noted (list nos. 1-10):
Comments:
Signature of Health Inspector/Assistant:

18.6.2 System assessment through sanitary inspection as a management tool

Sanitary inspections provide a useful management tool for communities, water supply agencies and surveillance bodies. The value of the sanitary inspection is that it provides a longer-term perspective on the risks of contamination, gives an overview assessment of how effective operation and maintenance has been and which system upgrade is needed. Such information can help in directing resources for improvement of the infrastructure and for improved training of water supply operators. Sanitary inspections also provide an additional means of assessing the differences in water quality from different types of water sources thus helping overall national and regional planning and policy-making (Bartram, 1999; Howard, 2002). This type of analysis is likely to be undertaken by a utility or surveillance body rather than an operator of a supply.

In a number of countries, the combined analysis of sanitary risk scores and level of contamination has proved to be an effective way of prioritizing which water supplies receive investment (Lloyd and Helmer, 1991; WHO, 2004). In many cases there is a broad relationship between the overall sanitary risk score and level of contamination (Lloyd and Bartram, 1991; Lloyd and Helmer, 1991). However, such approaches do not necessarily identify which are the most important specific factors to address as the system of sanitary inspection provides each risk factor with equal weighting, despite awareness that this is unlikely to be the case.

It is often useful to be able to determine the importance of different risk factors in order to direct investment and action on those improvements in the source that will yield the greatest improvements in water quality. Such an approach is often particularly useful in order to assess whether microbial contamination of groundwater derives from poorly sited and constructed sanitation facilities or from poor maintenance of sanitary completion measures. Leaching from on-site sanitation has been identified in some cases to be the major cause (Boonyakarnkul and Lloyd, 1994; Rahman, 1996; Massone *et al.,* 1998; Melian *et al.*, 1999). Other research from a number of countries indicates that poor sanitary completion was more important in microbial contamination than subsurface leaching from hazards such as pit latrines (Gelinas *et al.*, 1996; Cronin *et al.*, 2002; Howard *et al.*, 2003) as described further in Section 18.6.3 below. This is particularly the case in situations where there are a number of sources of human faecal matter in the environment such as refuse pits and dumps, open defecation and widespread occurrence of animal faecal matter (Barrett *et al.*, 2000b; Chidavaenzi *et al.*, 2000). Furthermore, it is often important to determine the influence of other factors such as rainfall and population density, which may affect contamination risks (Wright, 1986; Gorter *et al.,* 1995; Barrett *et al.*, 2000a; Howard, 2002).

18.6.3 Establishing the importance of different risks due to poor sanitary completion

There are a number of approaches that have been used to investigate the relationships between individual risks identified through sanitary inspection and water quality outcomes using statistical methods to analyse the data. These approaches range from the use of simple reporting of the frequency of risks in relation to specified water quality targets to the use of contingency tables and logistic regression. In order to undertake such analysis, it is important that water quality data and sanitary inspection data are available and can be paired.

In undertaking analysis of the relationship between sanitary risk factors and water quality outcomes, it is useful to compare risks in relation to water quality targets, as the failure to meet specified targets would trigger action. Cronin *et al.* (2002) present the analysis of data from two sites in Kenya and Mozambique, where the frequency of reporting of individual risks identified in inspections of sanitary completion measures were compared against samples with results above and below the median concentration of thermotolerant coliforms. This is shown in Table 18.1 below. This analysis indicated that poor sanitary completion of wells was more important in leading to contamination than subsurface leaching from sources of faecal material.

Table 18.1. Risk factors relating to higher levels of microbial contamination in dug wells in Kisumu, Kenya (based on Cronin *et al.*, 2002)

Risk factor	**Percent of samples < median TTC/100 ml**	**Percent of samples > median TTC/100 ml**	**Difference**
Plinth <1.5 m	83	100	+17
Well wall sealed	83	91	+8
Surface waste within 30 m	83	91	+8
Ponding on plinth	50	55	+5
Drainage channel inadequate	100	100	0
Well cover unsanitary	92	91	-1
Latrines within 10 m	55	58	-3
Open water within 20 m	64	67	-3
Ponding within 3 m	92	82	-10

Other analyses have used concentrations of indicator organisms in water to define a water quality target based on international guidelines or national standards. In this approach, for each risk factor the difference in frequency of reporting of each risk factor is compared between when the target is met and when it is exceeded with the difference providing an indication of whether there is a relationship and the strength of relationships found. Howard *et al.* (2003) describe such an analysis of water quality and sanitary risks in shallow protected springs in Kampala, Uganda shown in Table 18.2.

It is often useful to undertake further analysis of the data to assess the strength of the relationships between risk factors and water quality. In studies from Thailand, Boonyakarnkul and Lloyd (1994) developed a Sanitary Hazard Index (SHI), which related the intensity of faecal contamination associated with individual risk factors identified from sanitary inspection. These authors were able to identify which factors had the highest SHI and concluded that this should provide direction in relation to the priority accorded to reducing the presence of individual risk factors. The authors noted that there was a difference between those factors with the highest SHI and those that were most commonly reported.

Combined analysis of water quality and sanitary inspection data can also be undertaken using a range of non-parametric tests, which is common in the analysis of water resources data (Helsel and Hirsch, 1992). The use of dedicated software packages will assist in undertaking such analysis, but are not essential. Such analysis often incorporates other data such as rainfall and population density that are considered important in controlling quality.

Table 18.2. Sanitary inspection and water quality data for protected springs in Uganda

Risk factor	Percent reported when <1 cfu/100 ml	Percent report when ≥1 cfu/100 ml	Difference
Masonry defective	8	17	+9
Backfill eroded	29	67	+38
Collection area flooded	79	83	+4
Fence faulty	83	100	+17
Animal access within 10 m	79	100	+21
Latrine less than 30 m uphill	4	0	-4
Surface water collects uphill	46	100	+54
Diversion ditch faulty	79	100	+21
Other pollution uphill	46	83	+37

One example of non-parametric statistical tests is a contingency table of odds ratios. To make this analysis, variables with continuous data (e.g. water quality, rainfall and population density) must be converted into binomial categorical data. In the case of water quality targets the resulting variable will be whether the target was complied with or was exceeded (often simply expressed as either Yes or No). For rainfall data, a new variable may be whether rain was recorded within a specified time period or whether a certain depth of rainfall occurred.

An example of a contingency table is given below in Table 18.3 taken from analysis performed by Howard *et al.* (2003), which combines analysis of sanitary risks and water quality objectives for faecal streptococci and thermotolerant coliforms in protected springs in Uganda.

In the example of Table 18.3, two water quality objectives have been selected to allow the data to be analysed: the absence of faecal streptococci and less than 10 cfu/100 ml thermotolerant coliforms, the latter being a more realistic target for non-chlorinated community-managed water supplies. Odds ratios exceeding 1 show a positive relationship between the risk factor and exceeding the water quality target.

For both water quality targets the analysis demonstrates that localised pathways combined to sources of pollution and rainfall lead to contamination. Furthermore, in this setting thermotolerant coliform contamination appears to result from a more complex set of factors than faecal streptococci but is still primarily linked to poor sanitary completion.

This data can be further analysed through logistical regression (Howard *et al.*, 2003). Using the same data shown in Table 18.3, logistic regression models were developed and are shown in Table 18.4. The regression models included all co-variates where odds ratios showed relationships significant at least to the 95 per cent level. Although not significant at least to the 95 per cent level for faecal streptococci, latrine proximity within 30 m was forced into the model as this was still deemed a plausible route of contamination.

Table 18.3. Contingency table for protected springs in Uganda (adapted from Howard *et al.*, 2003)

Variable	**FS >0 cfu.100ml^{-1}**			**TTC >10 cfu.100ml^{-1}**		
	Odds ratio	p	95% CI	Odds ratio	p	95% CI
Faulty masonry	1.216	0.475	2.42	1.506	0.075	1.4
Backfill area eroded	4.135	0.000	5.8	2.762	0.000	2.73
Collection area floods	0.619	0.085	0.71	0.603	0.035	0.53
Fence absent or faulty	9.492	0.008	48.26	3.496	0.138	17.64
Animal access <10 m	3.627	0.202	25.73	1.366	0.756	9.64
Surface water uphill	2.203	0.014	2.95	3.933	0.000	4.36
Diversion ditch faulty	0.755	0.369	0.98	1.324	0.263	1.35
Other pollution uphill	3.75	0.041	12.3	5.728	0.029	26.23
Latrine <30 m uphill of spring	1.938	0.057	2.85	1.759	0.036	1.94
Latrine <50 m uphill of spring	0.838	0.531	0.98	0.738	0.198	0.17
High population density	4.49	0.000	5.43	4.708	0.000	4.75
Waste <10 m uphill of spring	1.971	0.028	2.53	2.557	0.000	2.63
Waste <20 m uphill of spring	2.437	0.001	2.78	3.085	0.000	3.03
Waste <30 m uphill of spring	1.547	0.191	2.17	1.896	0.031	2.4
Rainfall within previous 2 days	4.966	0.000	6.29	3.827	0.000	3.75

Table 18.4. Logistic regressions for protected springs in Uganda (adapted from Howard *et al.*, 2003)

Model	**Model log estimate**	**Variables**	**Log estimate**	**Standard error**	**df**	**p-value**
Faecal streptococci >0 cfu/100 ml	343.27	Constant	2.63	0.36	1	<0.001
		Eroded backfill	-0.8	0.29	1	0.006
		Faulty fence	-1.94	0.88	1	0.027
		Surface water uphill	-1.07	0.32	1	0.001
		Rainfall within 2 days	-1.34	0.27	1	<0.001
Thermotolerant coliforms >10 cfu/100 ml	338.11	Constant	2.06	0.37	1	<0.001
		Eroded backfill	-0.72	0.34	1	0.034
		Collection area flooded	0.57	0.29	1	0.047
		Surface water uphill	-0.7	0.32	1	0.031
		High population density	-1.02	0.35	1	0.003
		Rainfall within 2 days	-1.64	0.29	1	<0.001

Both regression models indicate contamination resulting from rapid recharge close to the springs and suggest that it is poor sanitary conditions at the spring itself that represent the greatest problems for the microbial quality of water. It is likely that this occurs through both direct inundation and very rapid recharge through preferential flow paths. In both cases, the principal sources appear to be waste dumps and surface water rather than latrines. This agrees with other studies that point to the importance of refuse dumps for the presence of indicator organisms (Chidavaenzi *et al.*, 2000). In a study of wells in rural Mozambique, Godfrey *et al.,* (2005) found that there was a pulse response of microbial contamination to rainfall events. Soil and engineering studies indicated that localised pathways were likely to be the primary cause of contamination rather than contamination due to aquifer pathways (Godfrey *et al.*, 2005).

The findings of Howard *et al.,* (2003) and Godfrey *et al.*, (2005) are in agreement with other studies into the causes of microbial contamination of shallow groundwater supplies, which have tended to emphasize direct ingress rather than subsurface leaching of contaminants in causing contamination (Rojas *et al.*, 1995; Gelinas *et al.*, 1996). These findings emphasise the importance of sanitary completion of groundwater sources.

The influence of sanitary completion on controlling quality may vary with different technologies and areas. For instance, studies in Thailand by Boonyakarnkul and Lloyd (1994) concluded that on-site sanitation factors led to the greatest Sanitary Hazard Index and were therefore priority risks to resolve. In Uganda, the major control on quality in tubewells appeared to be the proximity and location of on-site sanitation rather than wellhead completion (Howard *et al.*, 2003). By contrast, studies in Bangladesh reported that wellhead completion was more important than subsurface leaching from on-site sanitation (MacDonald *et al.,* 1999; Ahmed *et al.,* 2002).

The results of these studies support the validation of control measures, an essential step within a WSP (see Chapter 16). The performance of a WSP may be assessed by repeating the above analysis after upgrading sanitary completion to address faults. identified.

18.7 CONTROL MEASURES FOR SANITARY COMPLETION OF GROUNDWATER SOURCES

The design, construction, operation and maintenance requirements for groundwater sources can be translated into a series of control measures or points at the wellhead or spring protection works. Key control measures for different types of groundwater source are shown in Table 18.5 below. Planning measures to control the presence of hazards in the catchment area or immediate vicinity of a well or spring are discussed in more detail in Chapters 18-25.

NOTE ▶ *In water supplies developing a Water Safety Plan (Chapter 16), system assessment would identify which control measures exist, their effectiveness and which need to be upgraded or newly introduced. Management plans would document why specific control measures were chosen, how their performance is monitored and which corrective action should be taken both during normal operations and during incident conditions when monitoring indicates loss of control.*

Table 18.5. Examples of control measures for sanitary completion and options for their monitoring and verification

Process step	Examples of control measures for sanitary completion	Options for their monitoring and verification
PLANNING	Plan site and depth of abstraction to avoid presence of hazards and pathways for their ingress into the water source, e.g. prevent presence of faecal material within set-back distance	Review (applications for) permits for construction of new abstraction facilities or for reconstruction and upgrade of existing ones
	Plan pumping regime to avoid leaching of contaminants into the aquifer by providing sufficient distance from sources of contaminants	
DESIGN AND CONSTRUCTION	Ensure good drainage around wellhead or spring, e.g. • with ditches to divert runoff away from the wellhead or backfill area of a spring • for wells with an apron to direct spills away from the wellhead • for springs with good drainage of wastewater away from the spring area	Sanitary inspection of design and condition
	Design wellhead or spring area protection to prevent direct contamination, e.g. with • Fencing to exclude animals from wellhead or spring backfill area • apron extending around the wellhead at least 1 – 1.5 m from casing • for boreholes ensure that join between apron and casing or lining is sound • for dug wells ensure wellhead is raised by at least 0.3 m and covered by slab • for springs ensure backfill area behind spring box or retaining wall is protected, e.g. with grass cover	
	Ensure sanitary completion of lining, e.g. • with lining extending at least 30 cm above the apron • with seal sufficiently extended below ground level: at least 1.5 m for boreholes with handpump and 5 m for mechanised boreholes • for boreholes with rising main in good condition • for dug wells by proper construction and use of mortar seal on lining, ensure lining stays in good condition (no weep holes during rainfall !)	
	Ensure adequate choice and good condition of structures, e.g. • for boreholes that pumps are firmly attached to the wellhead • for dug wells install handpump or other sanitary means of abstraction	
OPERATION AND MAINTENANCE	For boreholes and wells, ensure pumping regime does not exceed amounts allowed for during planning	Meter or estimate amount of water abstracted
	For dug wells ensure hygienic use of handpump or other means of withdrawing water	Regular inspection of condition and of use. Periodic analysis of microbial indicators.
	Ensure regular maintenance and cleaning of well or spring environment, e.g. removal of debris blocking diversion ditches or those removing wastewater from the vicinity of springs; repair of fences; repair of structures such as aprons, covering flaps, handpumps	Review inspection reports for compliance to management plans. Periodic analysis of microbial indicators.

Table 18.5 focuses on control measures for the design and construction of wells and springs which are specific to sanitary completion. For the operation of abstraction facilities, maintenance and repairs are crucial control measures for keeping contaminants out, and management plans to define the scope and timescales of such activities are important to support that they are regularly carried out.

Regardless of whether or not any of these control measures are part of a WSP, their monitoring and verification is crucial to ensure that they are in place and are effective. Table 18.5 therefore includes options for surveillance and monitoring of the control measure examples given. As most of the control measures for sanitary completion involve issues of design and maintenance, many of them are most effectively monitored by regular inspections and through reviewing inspection and maintenance reports. The periodic analysis of microbiological indicator organisms is also crucial to the verification and validation of protection measures. In this context, management plans are an important tool to ascertain that inspection and maintenance activities are regularly carried out. This aspect of monitoring focuses on checking whether the controls are operating as intended, rather than on contaminant concentrations in groundwater.

NOTE ▶ *Options for monitoring suggested in Table 18.5 focus on the control measures rather than on groundwater quality.*

Comprehensive groundwater quality monitoring programmes are a supplementary aspect of verification of the efficacy of sanitary completion.

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19

Hydrological management

J. Chilton and W. Alley

The management of groundwater resources is a broad and complex subject. Basic elements of hydrological management include water conservation measures to keep abstraction at a sustainable level or economic analysis of over-exploitation impacts. The lack of water suitable for domestic uses can have serious public health consequences, and the health sector may need to ensure that domestic water requirements are taken account of in overall water resources management. This may include, for example, participating in the negotiation of groundwater allocations with competing users, such as the agricultural sector.

The overall sustainable management of water resources, i.e. the quantity of water available for use, is largely outside the scope of this monograph. However, there is often a relationship between groundwater quantity and quality, and there are some situations and circumstances in which poor management of groundwater resources can have consequences for groundwater quality that, as pointed out in Chapter 8, can be severe and sometimes difficult and costly to reverse. This chapter briefly discusses management approaches to dealing with the types of groundwater resources degradation outlined in Chapter 8.

Effective management of groundwater resources requires integration of the most important hydrogeological and socioeconomic elements that determine the interactions between land and water use and groundwater systems. The functions required for management need to be identified, and if they are not already enabled through existing

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institutions, these may need to be strengthened or new institutional arrangements developed to allow appropriate combinations of legal, social and financial instruments to be used to manage groundwater resources. A more detailed discussion of the institutional issues related to groundwater resource management can be found in Chapters 5 and 7 as well as in Feitelson and Haddad (1998), Salman (1999) and Foster *et al.* (2000).

NOTE ▶ *This chapter introduces options for controlling risks potentially caused by abstraction through hydrological management. 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 often have a key role in hydrological management, but in many settings, other stakeholders also abstract groundwater. In such settings, the definition of control measures for hydrological management will require close collaboration of the stakeholders involved, including public authorities.

19.1 MANAGING ABSTRACTION TO PREVENT SALINE INTRUSION

A major quality issue caused by poor groundwater management is saline intrusion (see Chapter 8.6.2). There are numerous examples of saline intrusion where heavy groundwater abstraction from productive coastal limestone or alluvial aquifers for urban, industrial or agricultural usage has produced serious intrusion of saline water into these aquifers, often stretching far inland, and one example is given in Box 19.1.

The widespread prevalence and costly economic consequences of severe saline intrusion have led to the development of sophisticated approaches to its investigation, particularly by means of geophysics and numerical modelling, and to its management and control. The most obvious and technically easiest approach to managing saline intrusion is to restrict pumping to allow natural recharge from the hinterland to help maintain or re-establish natural conditions. If urban, commercial and agricultural activity in the coastal zone has become dependent on groundwater then this is economically and practically difficult to do. Reducing groundwater abstraction may require a combination of regulatory and fiscal measures (Salman, 1999), including licensing and charging for abstraction, raising energy prices or reducing subsidies, licensing and controlling new borehole construction and managing crop prices, imports and exports. A useful introduction to these options is provided by Foster *et al.* (2000).

Box 19.1. Saline intrusion in the Greater Jakarta area

The population of Greater Jakarta has risen from 1.5 million in 1950 to an estimated 11-12 million in 2004. This rate of increase is typical of cities in the region and, in this situation, water supply provision is a continuous challenge with respect to both quantity and quality. In 1985 the total water demand of the city was 450 million m^3 and was met by surface water from rivers and reservoirs and from groundwater. Some 200 million m^3 were drawn by innumerable shallow wells and 50 million m^3 from deep wells. The latter is estimated to have risen to 70 million m^3 by 2000.

Hydrogeological setting: The base of the aquifer system in the Greater Jakarta area is formed by consolidated Miocene sediments, which outcrop at the southern boundary of the basin (Figure 19.1). The material filling the basin consists of marine Pliocene and Quaternary fan and delta sediments that are up to 300 m thick. Thin sandy layers, only 1-5 m thick, interbedded within the predominantly silty and clayey sediments form the productive parts of the aquifer system (Djaeni *et al*., 1986). On the basis of the vertical variation in hydraulic conductivity in these sediments, the overall system can be divided into a shallow unconfined aquifer zone down to 40 m, a middle zone from 40 m to 140 m and a deep, strongly confined aquifer zone below 140 m.

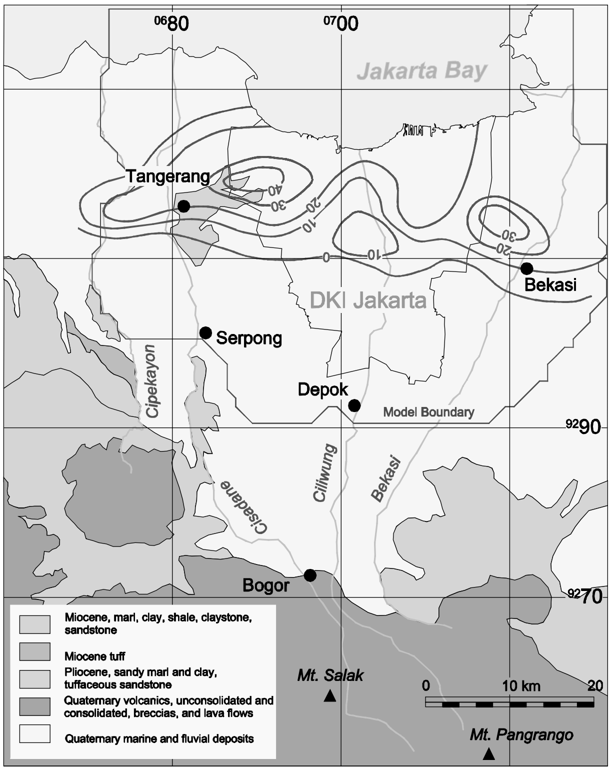

Figure 19.1. Geology of the Jakarta-Bogor area

Impacts of abstraction on groundwater levels: In 1900 the groundwater pressure head in the deep aquifer was at 5-15 m above sea level in the northern and central districts of Jakarta, and the few existing wells were generally overflowing. From 1900 to 1970, piezometric heads dropped at 0.1-0.2 m/a, increasing to more than 1 m/a in some areas of the city by the 1980s, and had dropped to 10-40 m below sea level by 1997 (Figure 19.1).

Groundwater in the deep aquifer moves from the recharge area in the south which has an average annual rainfall of 2900 mm, to the discharge area of the coastal plain with an average rainfall of about 1700 mm/a. This rainfall is more than enough to replenish the shallow aquifer in normal rainy seasons, although in dry years the combination of increased abstraction and lack of recharge causes some water table decline in the shallow aquifer. However, the lateral inflow of about 15 million m^3/a does not balance the abstraction referred to above, and the continuous drop in piezometric head indicates that downward leakage cannot balance the abstraction either because the vertical hydraulic conductivity of the confining layers is only 0.001 m/d. The area of groundwater depletion continues expanding laterally and vertically, and land subsidence is beginning to occur as a result (CCOP, 1999).

Impacts on groundwater quality: The groundwater chloride content ranges from 200 mg/l in the south to 600 mg/l further north (CCOP, 1999). The shallow aquifer suffers from saline intrusion extending 3-6 km inland from the coast, and is also affected by the infiltration of polluted recharge water, especially in the industrial areas and the most densely populated parts of the city. The deeper aquifer is less severely affected and in the coastal zone there appears to be quality stratification, with saline water in the upper aquifer (less than 100 m below ground), relatively fresh water from 100 m to 200 m and increasing salinity again below this depth.

Managing the impacts of abstraction: The seawater encroachment would be more pronounced if the hydraulic conductivity of the sediments was greater. The aquifer system has been modelled to help define management and monitoring requirements. Further increases in groundwater abstraction would have major negative impacts on an already serious situation. Management recommendations include moving the centres of groundwater abstraction southwards further from the coast, and gradually closing down production wells in the area endangered by saline intrusion.

A variant of controlled abstraction was introduced in the Chalk aquifer on the south coast of England in 1957, following the very dry summers of 1949 and 1956 in which water levels declined dramatically and saline intrusion threatened, especially around Brighton (Headworth and Fox, 1986). In winter, when there is recharge and the most active groundwater flow is towards the sea, pumping takes place from boreholes close to the coast to intercept this flow without causing saline intrusion. In summer, at times of lower groundwater levels and less active flow, the coastal wells are rested to reduce the danger of saline intrusion and pumping takes place further inland, exploiting the storage in the aquifer. As a result, average groundwater levels close to the coast have recovered by 4-5 m. Although there are significant additional costs for pumping and distribution, which are taken account of in the abstraction scheduling, the overall policy has worked well because service reservoirs in the distribution system have been closely controlled to optimize pumping, the new supply sources added have allowed the abstraction to be better distributed and the general lack of private supply boreholes helps to permit comprehensive management by the water utility (Jones and Robins, 1999).

As an alternative to reducing abstraction, methods of increasing local recharge close to the coast have been developed. Novel methods include the use of seepage barriers by placing recharge basins or lines of recharge wells between the coast and the areas of groundwater abstraction. These help to restore groundwater levels by creating an artificial recharge mound, which increases heads and pushes the saline interface down and back towards the coast.

Another method involves the use of abstraction barriers, by pumping from a line of defence wells to form a cone of depression in the water table between the coast and the valuable freshwater abstraction sources further inland, to intercept the saline water.

All of these control measures require regular monitoring to check that they are in place and functioning. They also require validation to check their effectiveness through groundwater quality monitoring. As this can usually be done simply by measuring electrical conductivity, monitoring is relatively inexpensive, either from regular field measurements of discharged groundwater or by observing the movement of the saline interface in suitably located observation boreholes. To support adequate monitoring being carried out, monitoring regimes are best explicitly defined in management plans.

19.2 MANAGING ABSTRACTION TO CONTROL INDUCED POLLUTION

The widespread occurrence in thick aquifer sequences of downward leakage of shallow polluted groundwater to deeper horizons providing public supply is also mentioned in Chapter 8.6.2. This leakage may be induced or accelerated by heavy and prolonged pumping from depth, such that polluted groundwater penetrates to depth more quickly than anticipated. In the case of Santa Cruz illustrated in Chapter 8.6.2, however, using chloride and nitrate as indicators of the polluted water, the pollution front does not appear to have penetrated below about 90 m depth (Morris *et al.*, 2003) despite the heavy pumping from the deep public supply boreholes. This is probably because the continuing abstraction from the shallow aquifer for private water supplies intercepts, abstracts and recycles a proportion of the shallow, polluted water. Though in this case the situation developed coincidentally, this is what good management of this aquifer system would require and, provided that the shallow groundwater is not used for potable supply, both the shallow and deep groundwater abstraction are able to continue.

In such situations, controlling abstraction will be only one option in a range of possible approaches to managing groundwater quality. In the Santa Cruz case, other management activities that would improve the situation would be directed at reducing the pollutant loading. Measures would include, for example, extending mains sewerage to the most vulnerable and permeable strata underlying the urban area to reduce the loading from unsewered sanitation, locating polluting industries away from these areas and/or improving their practice of handling pollutants and disposing of effluents, as well as using the planning process to encourage new city expansion over less vulnerable, clay-covered areas. Hydrological management may include encouraging the use of the shallow water for non-potable uses, lining wastewater or drainage canals or installing mains sewerage, and possibly the development of new wellfields beyond the urban boundaries to meet increasing demand.

Pollution of the upper part of an aquifer sequence threatening deeper potable supply boreholes can also occur in areas of intensive agriculture. In the United Kingdom, the impact of rising nitrate concentrations in groundwater has been felt first in the uppermost parts of the aquifers. When the problem was first observed, engineering solutions such as deepening the abstraction boreholes or increasing the length of casing to shut out shallow groundwater were advocated and tried. Because the impact of pollution on groundwater quality is such a long-term process, such engineering measures are at best temporary solutions, and reduced abstraction and blending with lower-nitrate water has become more common.

19.3 MANAGEMENT OF ARTIFICIAL RECHARGE AND WASTEWATER USE

The main purposes of artificial recharge of groundwater are to store surface water and reclaimed municipal wastewater or storm water for future use and to reduce, stop or reverse declines of groundwater levels, in order to prevent eventual exhaustion of the groundwater resource in the long term (Asano and Cotruvo, 2004). An aquifer can be used to store surface water in times of excess, which is recovered in times of shortage, particularly where the supply of water varies greatly over the year. Evaporation losses from underground storage are much less than from surface storage reservoirs, and environmental impact is likely to be lower. Artificial recharge can also be used to prevent saltwater intrusion in coastal aquifers and for oxygenation of an aquifer to change the quality of groundwater.

Recharge is also incidentally achieved, for example in irrigation and land treatment. Rivers and canals are often used to carry uncontrolled and untreated domestic and industrial effluents in and close to cities, and recharge from them, via unplanned percolation or infiltration, has a major impact on the underlying groundwater quality (Gooddy *et al.*, 1997; Morris *et al.*, 2003; Asano and Cotruvo, 2004). Recharge with wastewater – both designed and unintentional – may be an important element of the management of water quantity in an aquifer.

A broad range of technologies and methods is used to recharge the water into the ground. Artificial recharge is becoming increasingly important, and is a large and growing subject with an extensive literature (NRC, 1994; Asano, 1998; Dillon, 2002; Aertgeerts and Angelakis, 2003; Asano and Cotruvo, 2004).

19.3.1 Source water for recharge

Artificial recharge requires a sufficient and reliable source of water, and its choice is related to the anticipated usage of the additional groundwater resources. Source waters used in practice include rivers, collected rainwater, water previously used for cooling or heating purposes in production, water previously used for other purposes in production, or untreated or treated wastewater. In a review of 45 case studies of aquifer recharge, Pavelic and Dillon (1997) found that 71 per cent used natural source waters from rivers, lakes or groundwater, 20 per cent used treated sewage effluent and 9 per cent used urban storm water run-off.

Where there is a large variation through the year in the amount of available water for recharge, large storage volumes to cope with peak discharges may be required before recharge occurs. As wastewater is often predictably available irrespective of the seasons and climatic variations, it has great attraction as a source (NRC, 1994).

Surface water, storm water and particularly wastewater used for aquifer recharge usually contain a wide range of pathogens and chemical contaminants. Infiltration through the soil and unsaturated zone can greatly improve the quality (Bouwer and Rice, 1984; Idelovitch and Michail, 1984), and where artificial recharge is undertaken with poor quality water, the recharge process itself usually provides an element of water treatment. On the other hand, contaminants introduced through recharge may lead to long-term degradation of aquifer quality. The use of aquifer recharge therefore requires a careful assessment of the risk of degrading the groundwater quality, particularly if it is a source for drinking (see also Chapter 14). The nature and concentrations of pathogens and chemical contaminants (Chapters 3 and 4) present in the water used for recharge, aquifer vulnerability of the setting (Chapter 8), as well as recharge methods employed, determine the need and level of pre-treatment and the residence time necessary in the unsaturated zone for removal to be sufficiently effective so that the water can be used as drinking-water without a health risk. With some types of recharge techniques or installations, there may also be a health hazard at the surface, for example farmers irrigating with wastewater, animals and children playing at infiltration lagoons that are not fenced.

Particularly in those instances where disposal of wastewater is the primary objective and aquifer recharge is only an incidental or unintentional side-effect, little or no consideration may have been given to the possibility that infiltration of water and pollutants can have a major impact on the underlying groundwater. Improving the management of these for the objective of sustainable use of an aquifer as drinking-water resource will also require an assessment of current contamination as well as of aquifer vulnerability (see Chapters 8 and 14), and introducing or upgrading wastewater treatment prior to infiltration may prove necessary (see Section 19.3.2).

For wastewater, Table 19.1 shows a range of recharge techniques, proposes a level of treatment necessary to avoid aquifer degradation, and shows that, in many cases, the actual level of treatment falls short of that required to prepare the wastewater.

Table 19.1. Summary of wastewater treatment, use and disposal practices which lead to intentional or unintentional groundwater recharge (modified from Foster *et al.*, 1994)

Recharge technique/process	**Primary objective**	**Level of treatment**		**Ground-water recharge**
		Recommended	Frequently encountered	
Stabilization/oxidation ponds	Treat, dispose, sometimes treat/use	P, S	P	inc, acc
Infiltration well/lagoon/pit/trench		P, S	P, S	des, inc
Land-drain infiltration		P, S	S	des, inc
Land-spreading and evaporation		P, S	R, P	inc
Agricultural/amenity irrigation	Use	P, S, T	R, P	inc, acc
Riverbed seepage	None	-	R, P, S	acc
Bank filtration	Treat/use	P, S	R, P, S	des
Deep injection wells	Dispose	P, S, T	S, T	des

R = raw, P = primary, S = secondary, T = tertiary, des = designed, inc = incidental, acc = accidental

19.3.2 Recharge techniques

For recharge to be sustainable and safe, systems need to be suitable for the water types available and the underlying hydrogeological conditions, and the choice of site and system are important control measures (see Chapter 19.6). Techniques for applying water for infiltration include well injection, sprinkling onto the land surface and infiltration basins

Well injection does not retain contaminants through soil filtration. This technique is often used where groundwater is deep or where the topography or the existing land use makes surface application impractical or too expensive; or when direct injection is particularly effective in creating freshwater barriers in coastal aquifers against intrusion of saltwater (Asano and Cotruvo, 2004). Traditionally it consists of at least two wells, one for injection of the water and one for recovery of the recharged water. Recently, well injection that uses the same well for injection and recovery of recharged water, a technology known as aquifer storage and recovery, has become more commonplace. For conducting deep well injection safely, detailed hydrogeological information (e.g. extent of the aquifer, water quality in the aquifer, regional groundwater flow) are necessary and need to be carefully related to the quality of the water to be injected, particularly if the aquifer is used for drinking-water supply.

Sprinkling recharge water onto the land surface and allowing it to infiltrate downward into the unsaturated zone may effectively remove contaminants by the treatment effect of soils. This is a simple method suitable for water with a low suspended solid load, which only requires sprinkling equipment, a pump and pipes and hoses to deliver the water. The sprinkling system can be located at a fixed point, and water is sprinkled from that point by rotating the sprinkler around it. Another method is by moving the sprinkling point on a wagon/truck. By using a wagon or truck the water can be distributed more evenly at the surface than when sprinkling is limited to single points.

In basin infiltration the water is recharged from a basin created at the surface. Water is pumped into the basin from which it infiltrates slowly into the unsaturated zone. This is also a simple system where the only requirements are a pump and pipes/tubes to deliver the water, and an excavator to create the basin. One advantage of using a basin instead of the sprinkling system is that as long as the basin is filled with water the infiltration will continue at the maximum infiltration rate, provided the basin is maintained to avoid clogging.

19.3.3 Management of recharge to reduce pollution risk

A further requirement for artificial recharge to be effective is an adequate volume of permanent or seasonal groundwater storage to be able to accept the recharging water. The unsaturated zone requires a certain thickness so that slow infiltration allows sufficient residence time to achieve sufficient removal of the possible pollutants. The likelihood of pollution occurring depends on the scale and mode of infiltration, the quality of the water and the hydrogeological conditions, and it is necessary to understand the relationship between these to establish approaches to management that reduce the risk of groundwater pollution (see also Chapter 14).

Selection of scale and mode of infiltration

The selection of methods for recharge depends on many factors, including land availability, soil type, hydrogeological conditions, available finances and level of technology and the need for subsequent recovery of the water (Asano, 1998). The nature and hydraulic conductivity of the soil or subsoil and the required loading exercise major control over the method used. Wright and Rovey (1979) determined that for wastewater loading rates greater than 20 mm/d, basin or lagoon infiltration is applicable on sandy soils. Below this loading, over-irrigation and overland flow methods should be used, and can be applied on more silty or clayey soils. The former involves the application of excess irrigation loads and the latter implies allowing the applied water to flow over the irrigated land. The best soils for infiltration have hydraulic conductivities in the range 0.1 to 2 m/d. Below this range, very fine-grained soils will limit the rate of percolation and above this, coarse-grained soils permit rapid infiltration but the residence times may not be optimum for pollutant removal. The relationship between infiltration capacity of the soils and infiltration method (Foster *et al.*, 1994) and the availability of suitable land for the construction of facilities is thus a key factor in the planning process.

Quality of the infiltrating water

The quality of the water will also influence the effectiveness of recharge, and highly treated wastewater effluents or source water will infiltrate at the highest rates. As already mentioned above, pre-treatment may be necessary to remove particles (e.g. bacteria, algae or inorganic particles) or compounds that cause clogging of the injection wells, sprinkler systems or the upper part of the unsaturated zone. The purpose of such pre-treatment is to prolong the time a plant can function properly. Another pre-treatment process is the addition of oxygen if the water contains very high concentrations of organic material which have to be biodegraded, and the water does not contain sufficient oxygen for the removal process.

In some countries (e.g. the USA) aquifer recharge systems are legally required to use only treated wastewater effluents, even if contaminants from primary effluents would potentially be equally attenuated by infiltration and soil aquifer treatment (Lance *et al.*, 1980; Carlson, 1982).

Processes affecting water quality

During infiltration of recharge water, quality can undergo changes from the following:

- microbial constituents can be attenuated by filtration and sedimentation, and can grow or decay;
- organic compounds in the source water can be adsorbed onto, or ion exchange with, the soil particles, volatilize to the air phase, be subjected to biodegradation, and be chemically transformed;
- inorganic compounds can also be adsorbed to, or ion exchange with, the soil, volatilize to the air phase, be transformed by redox processes, precipitated or dissolved, and participate in biodegradation of the organic compounds;
- solids in the source water can be attenuated by filtration and sedimentation.

Chemical transformations are not generally important processes in these situations because the rates are usually very low compared to the residence time in an artificial recharge system. In contrast, growth and decay of bacteria always occur, and some of the most important pollutant attenuation processes in recharge (biodegradation of organic compounds) are enhanced by the presence of suitable bacteria. Provision of suitable organic substrate for bacterial activity may be one reason why the quality of primary effluent is as effectively improved as that of secondary effluent, and why there is a dilemma as to whether disinfection by chlorination before recharge is desirable, as it may destroy soil microbial populations that take part in the elimination processes. Some of the processes interact with each other: for example, carbon dioxide produced by biodegradation is an acid and consequently changes the pH of the system, which in turn affects microbial activity.

The use of soil aquifer treatment has been shown to greatly reduce bacteria and viruses, suspended solids, organic carbon, total nitrogen and phosphorus (Bouwer and Rice, 1984; Idelovitch and Michail, 1984; Jimenez and Chávez, 2004). Even when untreated wastewater is used primarily for irrigation, but with incidental recharge (Table 19.1), infiltration through the soil and unsaturated zone removes many or even most of the pollutants. In the case of the very extensive irrigation with collected but untreated wastewater in Mexico (Jimenez and Chávez, 2004), metals, organic carbon, nutrients and pathogens are at least partially removed in the distribution system, the soil and the aquifer. In detailed field investigations at Leon, salinity, the most unaffected and conservative of pollutants in the wastewater, was observed to have penetrated deep into the aquifer and affected the quality at 300-400 m deep public supply boreholes within the wastewater irrigated area (Chilton *et al.*, 1998).

Agricultural or amenity irrigation with wastewater makes maximum use of the attenuation properties of the soil. However, in many of the types of facilities listed in Table 19.1, the soil is disturbed or removed, and this will reduce the capacity for pollutant attenuation by the processes outlined above and described in more detail in

Chapter 4. This is why there is a clear relationship between type of facility used and level of treatment required.

Operational considerations in artificial recharge and wastewater use

Operational management of artificial recharge should be based on sound scientific understanding and follow a general multiple barrier approach. These barriers would include ensuring that the design level of treatment is adequate for the particular setting, is secure, verification that the expected improvement in quality in the subsurface does in fact occur, and that post-abstraction treatment in the case of potable supply use is also properly maintained. Among the most important aspects of the management of artificial recharge facilities is to ensure that the anticipated attenuation processes do indeed occur, and that nothing happens to lessen their effectiveness. In fact, management usually has three main objectives, which have to be balanced to optimize the operation of the scheme:

- maintain the efficiency of infiltration close to the rates envisaged in the design of the system;
- maximize quality improvement by the physical, chemical and biological processes outlined above;
- ensure avoidance of aquifer contamination.

These objectives can often be in conflict, as rapid infiltration may mean insufficient residence time for these renovating processes to operate. Thus if clogging of recharge basins is a problem which is managed by periodic removal of the clogged layer, then care has to be taken as the organic mat formed on the floor of the basin is a key component in the attenuation processes. Algal and bacterial growth in basins or in the water source used can also rapidly reduce infiltration rates, and may also encourage the precipitation of calcium carbonate or iron salts, which can seal lagoons or injection wells. Usually, this is limited to a zone a few centimetres thick. For injection wells, this is dealt with by conventional well rehabilitation methods and chlorination, and the precipitates may be removed from the well screens by introducing acids, agitating the mixture within the well and pumping out the residue.

For basins, clogging can be addressed by periodic drying out, or by removing the uppermost soil layer. In an empty basin or in a sprinkling plant the clogged soil can be taken away and discarded or the infiltration capacity can be regained by harrowing or ploughing. If the basin is full of water the clogged soil can be excavated by use of specially designed machinery or equipment. This has the advantage that the clogged soil can be taken away without disturbing the operation of the plant. Where specific organic compounds are removed from the recharge water by sorption to the soil of the basin rather than by biodegradation, attention is needed to potential saturation of the soil: if the soil's capacity for removing such contaminants is exceeded and cannot be regained, it can no longer be used for artificial recharge, and the topmost layer may need to be removed.

Management of the periodic flooding and drying of basins is a key factor in the success of wastewater recharge projects, as this controls the alternation of oxidizing and reducing conditions which are so essential to the biochemical processes involved in attenuating nitrogen from the recharge water (Bouwer and Rice, 1984). Schemes should be large enough and have sufficient separate basins to allow this to occur. In practice, the inflow volume often increases beyond the design capacity as growing urban areas generate more wastewater, and this compromises correct operation. The wetting and drying cycles themselves have to be carefully managed as, especially in very hot and arid climates, prolonged drying of the soil may damage the bacterial populations and decrease the efficiency of bacterial attenuation processes until they have a chance to re-establish themselves.

As these operational considerations are of critical importance for the safety of aquifer recharge schemes, the specific control measures identified for a given setting should be documented in a management plan together with the operational monitoring system that is to be used to ascertain that they continuously operate as specified (see also Chapter 19.6).

19.4 BANK INFILTRATION

Riverbank infiltration is a long-established method of obtaining drinking-water supplies by using the attenuation capacity of the subsurface close to a riverbed as a natural filter through which river water is drawn. In Europe, over 100 years of experience of bank filtration has accumulated since the first such installations at Düsseldorf on the Rhine and Nijmegen on the Waal in the 1870s. The review by Grischek *et al.* (2002) indicates the scale and importance of bank filtration. In the Rhine basin, some 20 million people receive their drinking-water supplies from bank filtration, and such facilities provide 45 per cent of drinking-water in Hungary, 50 per cent in Slovakia, 16 per cent in Germany and 5per cent in the Netherlands. Berlin is 75 per cent dependent on bank filtration of lake water, and the cities of Düsseldorf and Budapest are totally dependent on bank filtration. A useful summary of the features of selected bank filtration systems is given by Grischek *et al.* (2002).Bank filtration schemes usually consist of a gallery or line of wells or boreholes located parallel to and a short distance from a surface water body. Pumping lowers the groundwater level adjacent to the surface water body, inducing river water to move through the aquifer to the wells or boreholes. Current understanding of the processes of pollutant attenuation processes in bank filtration schemes is largely based on empirical knowledge. There are no common guidelines on the conditions necessary for the optimization and adequate protection of bank filtration schemes. As a rough approximation, minimum travel time approaches have often been used, i.e. that the wells or boreholes should be located at a sufficient distance from the river to allow 50 days flow time from riverbed to abstraction point (Grischek *et al.*, 2002), or 30-60 days as suggested by Huisman and Olsthoorn (1983). This has traditionally been considered sufficient for pathogen removal. The distance from the river bed to the abstraction wells is not directly reflected in the travel time, which also depends on the aquifer thickness, abstraction rates and the nature of the riverbed material. In practice, travel times range from a few days to more than ten years, and separation distances from a few tens of metres to several hundred metres (Grischek *et al.*, 2002). More recent risk assessment approaches differentiate between groups of pathogens and chemicals, and they measure or model the likely retention of contaminants in the underground of the respective setting in relation to the given conditions (see also

Chapters 3 and 4). As with other measures to reduce contaminant concentrations to safe levels it is important to validate the individual system’s performance against the quality targets given.

The factors which determine the success of bank filtration schemes are a reliable source of water in the river, acceptable river water quality, as well as sufficient permeability of the river bed deposits and the adjacent alluvial formations. Provided that the permeability of the stream bed and aquifer are high and the aquifer is of reasonable thickness, then large amounts of water can be abstracted from the wells without serious adverse affects on the groundwater levels on the inland side of the wells (Huisman and Olsthoorn, 1983).

It is possible to distinguish river water from groundwater at many such installations by the use of isotopic or chemical tracers. Investigators have used chloride, boron, ^{18}O and, more recently, organic and pharmaceutical compounds as tracers of the treated sewage component of major rivers. The proportion of water drawn from the river varies from 10 per cent to nearly 100 per cent, and is often more than 50 per cent. At least some of the water in a bank filtration well is inevitably drawn from the aquifer independently of the bank filtrate. It may then be necessary to protect the groundwater from pollution by imposing suitable source protection zones around the wells or line of wells. If the aquifer material is sufficiently permeable to permit large volumes of water to move through it from the river, it is probably also permeable enough to be vulnerable from pollution at the ground surface. It may be necessary, therefore, to impose controls on river water quality and, as in the case of the river bank filtration wells which provide part of Budapest's municipal supply, groundwater protection measures which impose some controls on urban and agricultural activities within their capture zones.

River waters often carry considerable amounts of suspended matter, which can be left on the river bed and cause clogging. To help prevent rapid clogging, the rate at which the surface water enters the aquifer should be kept low, which is why multiple abstraction points are normally used. Sometimes the banks and bed of the river are scraped or dredged clean during periods of low flow to remove accumulated silt, clay and organic matter, in much the same way as for artificial recharge basins mentioned above. As with infiltration basins for artificial recharge, this has to be done with care, as the filter skin formed on the bed of the river plays a key role in restricting pollutant transport, and its careless total removal might allow breakthrough of previously attenuated pollutants.

Bank filtration installations close to large rivers usually need to be well protected from the danger of flooding to prevent short-circuiting or direct ingress of polluted floodwaters. In many cases, this is achieved by bringing the well casing or caisson some distance above the permanent ground level, so that access is raised above likely flood levels.

19.5 VALIDATION OF ARTIFICIAL RECHARGE AND BANK INFILTRATION SCHEMES

Approaches to recharging aquifers with potentially contaminated surface water – and particularly those schemes involving wastewater use – require validation of the management approach to ensure that the water quality targets are met. Monitoring programmes for validation need to be tailored to the specific problems identified in a situation assessment for the given setting. For bank filtration, validation of the hazard analysis requires repeated sampling and analyses of surface water quality and of groundwater between the river and the abstraction boreholes or wells to investigate which pollutants may enter the groundwater flow pathway and how well they are attenuated before the water reaches the abstraction wells. For designed wastewater recharge schemes, validation would usually include analyses of the quality of the incoming wastewater, stages of the treatment process and the final water before use. The monitoring of the quality of recharge water and groundwater at established recharge schemes such as those in Arizona, USA (Bouwer and Rice, 1984) and the Dan region in Israel (Idelovitch and Michail, 1984) have provided much of the evidence for the long-term ability of soil-aquifer treatment to remove a range of pollutants, and these data are also valuable for validation of the design of the systems.

Depending on contaminants expected from the water used for recharge and/or infiltration, parameters for validation may include:

- microorganisms (e.g. faecal indicators or individual pathogens such as bacteria, viruses or protozoa);
- specific organic compounds expected to be present in water used for recharge;
- organic matter (TOC, BOD, etc.) especially if the recharge water is sewage;
- regular drinking-water parameters (pH, conductivity, nitrate, nitrite, ammonium, sulphate, iron, etc.);
- if present in high density in the surface water used, algae and cyanobacteria (cell counts);
- if cyanobacteria are present in high densities, the potential for breakthrough of their toxins should be assessed (e.g. through periodic screening following heavy blooms);
- suspended solids;
- in climates with seasonal change, water temperature as an indicator of the water's travel time.

19.6 MONITORING AND VERIFICATION OF CONTROL MEASURES FOR HYDROLOGICAL MANAGEMENT

Table 19.2 summarizes selected examples of the measures proposed above for ensuring sustainable groundwater supply without compromising its quality. These begin with planning the choice of sites for groundwater abstraction and determining permissible amounts in relation to natural recharge. Where artificial recharge or bank filtration schemes are intended, they should be planned and operated in relation to aquifer vulnerability. Checking that design and construction are conducted adequately – following the plans – is important because many of the structures for abstraction or artificial recharge are installed underground, where they will rarely be accessible for inspection later. Further, operational controls are critical to ensure that amounts abstracted are in compliance with plans and permits. Likewise, operational controls for artificial recharge or bank filtration address water volumes infiltrated as well as regimes for removing clogging layers.

Regardless of whether or not any of these control measures are part of a WSP, their monitoring and verification is crucial to ensure that they are in place and are effective. Table 19.2 therefore includes options for surveillance and monitoring of the control measure examples given. Most of these focus on checking whether the controls are operating as intended, rather than on contaminant concentrations in groundwater.

NOTE ▶ *The implementation of control measures in hydrological management such as the examples suggested in Table 19.2 is effectively supported if the stakeholders involved collaboratively develop management plans that define the control measures and how compliance is monitored, which corrective action should be taken both during normal and during incident conditions, responsibilities, lines of communication as well as documentation procedures.*

The implementation of control measures to protect drinking-water aquifers from quality impairments caused by abstraction is substantially facilitated by an environmental policy framework (see Chapter 20).

In addition to monitoring of the functioning of control measures, overall monitoring programmes are important to verify comprehensively that groundwater abstraction is not mobilizing contaminants or inducing saline intrusion. For artificial recharge or bank filtration schemes, groundwater monitoring is particularly important to verify that these are not introducing pollutants into aquifers used for drinking-water abstraction, i.e. that the management concept is adequate and safe. This would typically include faecal indicators and potentially pathogens of particular concern in the water infiltrated. Where surface water used for infiltration is contaminated by chemicals from industry, household use or small-scale enterprises, occasional validation of the efficacy of their removal would be part of a monitoring programme to ensure overall groundwater safety.

NOTE ▶ *Options for monitoring suggested in Table 19.2 focus on the control measures rather than on groundwater quality. Analysis of selected parameters in groundwater which indicate drawdown of the water table or migration of contaminants is suggested where this is the most effective operational control.*

Comprehensive groundwater quality monitoring programmes are a supplementary aspect of monitoring with the purpose of providing verification of the efficacy of overall drinking-water catchment management.

Table 19.2. Examples of control measures for hydrological management and options for their monitoring and verification

Process step	Control measures for hydrological management	Options for their monitoring and verification
PLANNING	Plan abstraction and manage demand in relation to rates of recharge to ensure sustainable use (incl. in relation to amounts used by other stakeholders, e.g. for irrigation)	Review (applications for) permits for construction of new wells Monitor and record volumes abstracted Conduct tests with tracers and/or indicator organisms to validate adequate choice of site
	For artificial recharge or bank filtration: determine adequate design and choice of site in relation to the quality of river water used and pollutant attenuation in the subsoil	Monitor quality of surface water infiltrated Validate contaminant removal efficiency
	For some settings with seasonal recharge: establish seasonally variable abstraction regimes adapted to recharge patterns	Monitor groundwater levels Monitor discharge, conductivity and/or movement of saline interface
	Develop water conservation measures to help limit abstraction	Monitor water usage of different users (e.g. domestic, incl. mains leakage, irrigation and industry)
DESIGN AND CONSTRUCTION	For bank filtration: ensure adequate protection of wellheads to avoid contamination through flooding	Wellhead inspection as described in Chapter 17
	To avoid saline intrusion: establish hydraulic barriers, e.g. through defence wells or pumping regimes	Monitor operation of defence wells and pumping regimes Monitor movement of interface of saline/non-saline groundwater (e.g. through conductivity recording in observation wells)
OPERATION	Control abstraction in relation to recharge	Record volumes abstracted Monitor groundwater levels Maintain licensing system and abstraction records
	For artificial recharge and bank filtration: quantity management to maintain quality (i.e. functioning attenuation processes), e.g. through preventing hydraulic overloading and/or adapting amounts to seasonal patterns	Record quantities delivered to recharge facility and quantities abstracted Monitor infiltration rates
	For artificial recharge and bank filtration: ensure performance through adequate maintenance of facilities to avoid clogging of pores, as well as break-through of contaminants	Monitor quality of recharge water Record frequency and depth of removal of clogging layer and monitor infiltration rates particularly after removal
	For control of downward moving polluted groundwater: intercept through abstraction of shallow groundwater	Record volumes of shallow groundwater abstracted Early warning monitoring of an easily recorded parameter which indicates shallow groundwater reaching deeper aquifer horizons

19.7 REFERENCES

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