Section V

Approaches to pollution source management

20

Policy and legal systems to protect groundwater

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This chapter deals with the policy and legal environment within which groundwater protection and management should operate. Effective policies for groundwater protection must take account of the institutional and cultural environment in the country, the interrelationship of quantity and quality of groundwater, financial viability of any proposed measures for protection and acceptability of the measures to society. Policies that are considered reasonable in some countries may not be acceptable in others. Therefore, where proposed policy builds on experience elsewhere, it is important that local values of the society are taken into account. For this reason, it is essential that effective policy development includes the public, government agencies and other stakeholders potentially affected at the earliest possible stage.

The overall process of developing and implementing policies and strategic management for groundwater protection may follow the route shown in Figure 20.1.

While step 3 of this process is discussed in some detail in Chapters 5 and 7 and criteria for developing specific protection concepts are discussed in Chapter 17, this chapter reviews the overall framework of governmental policy and institutions that facilitates their implementation. Such a framework provides an important context in

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which fragmental local initiatives and actions can be amalgamated in to a comprehensive national or regional policy.

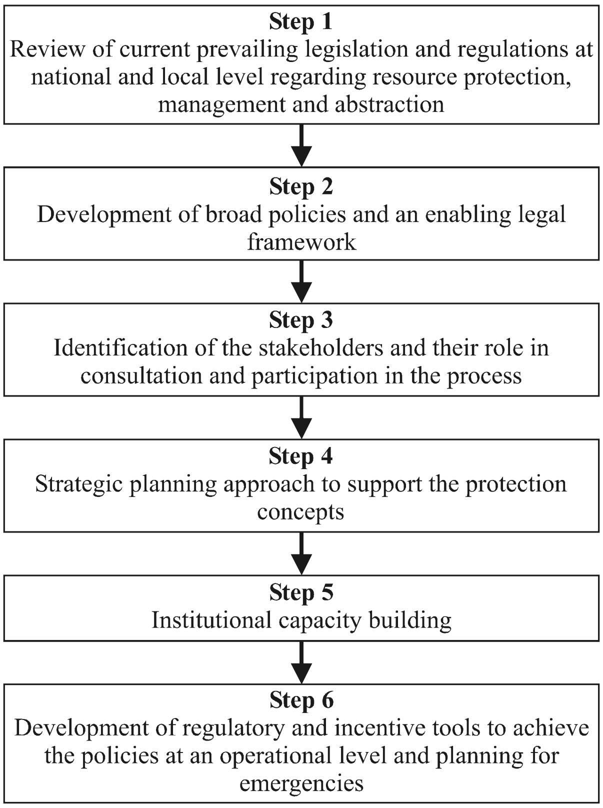

Figure 20.1. Flow chart for developing groundwater protection policies

20.1 GROUNDWATER PROTECTION POLICIES

Policies need to be applied in a properly understood and constituted framework so that their application is clear and their effectiveness is assured. OECD (1989) developed the DPSIR causality framework (shown in Figure 20.2) to enable the basic issues in policy development to be identified and possible impacts of proposed solutions to be tested. The DPSIR framework involves five principal steps. The Driving forces describe the human activities, such as the intensification of farming and chemical industry production or development of land for housing, which may lead to significant threats to the groundwater quality or quantity (as described in Section II). The Pressures describe the stresses that the developments place on a particular aquifer in terms of its possible uses. The State of the aquifer is described in terms of its quality and hydraulic condition and the Impact shows the outcome of loss of the source, for example the need to find alternative drinking-water sources if an aquifer becomes unusable. Responses describe the policies that have been or are being developed to deal with the problem. By using the DPSIR cycle it is possible to decide which of several alternative policies might be the optimum solution. Although not directly included within the DPSIR framework, processes to review effectiveness of responses are also critical (see Chapters 15 and 16).

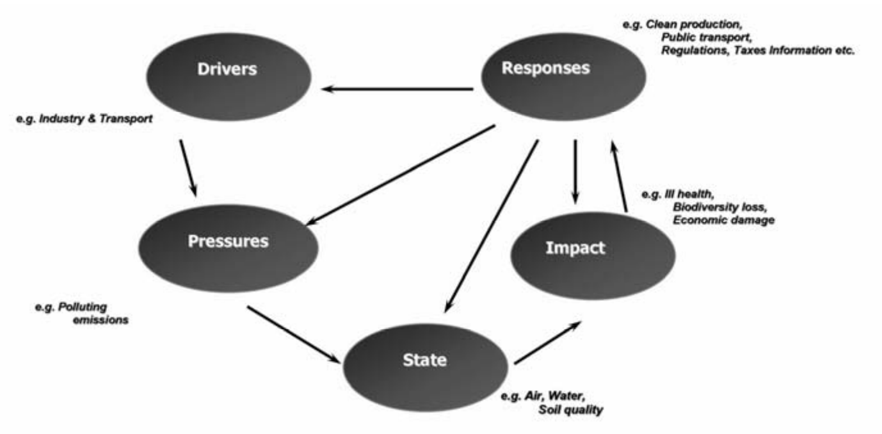

Figure 20.2. DPSIR framework (EEA, 1998)

UNECE (2000) has described how this approach is incorporated in the policy development as being a set of seven key steps:

1. Identify the functions or uses of the groundwater.
2. Identify the issues and problems (particularly health related problems).
3. Establish a function-issues table to see whether the issues are in conflict with the functions of the groundwater systems.
4. Establish management objectives using the function-issue table for priority setting based upon urgency and technical/financial means (see also Chapter 15).
5. Ensure that suitable information is collected on place and time dependent factors (on the groundwater body, the stages of the management programme, etc.), as discussed in Chapter 6.
6. Use the DPSIR concept to examine the detailed relationships and causalities.
7. Make a checklist with criteria that have to be met linked to the measurable factors identified above.

The European Union's Framework Directive for Water as one example of policy for groundwater protection – in this case not primarily targeting its use as drinking-water source – is described in Box 20.1.

Box 20.1. Example of policy for groundwater protection – European Union Framework Directive for Water

The European Union (EU) water policy has been based on six basic principles:

- a high level of protection;
- application of the precautionary principle;
- the prevention of pollution;
- the rectification of pollution at source;
- adoption of the polluter pays principle;
- the integration of environmental protection into other policies such as agriculture, transport and energy.

In the context of the application of these principles to the protection of groundwater, in 1992 the Council of Ministers (Resolution 92/C 59/02, OJ C59/2 6.3.92) recognized the dangers of falling groundwater levels and long-term problems associated with the pollution of certain aquifers, e.g. for providing drinking-water. As a result the Commission revised the Groundwater Directive by incorporating it into a general freshwater management policy.

Consequently, the EU has adopted a new approach to water policy. The Water Framework Directive (EU, 2000) expands the scope of water protection to all waters, surface waters and groundwater and requires the achievement of 'good status' for all waters by a certain deadline. The regime will require the overall management of water based on river basins, with a combined approach of using emission limit values for the control of discharges and water quality standards applicable to the natural waters. The Directive also concerns water pricing and ensuring that the citizen is more involved in decision taking.

The main features of this policy, which Member States of the EU will be obliged to transpose into their domestic legislation, include the recognition that underground water, as part of the whole water cycle, plays a part in maintaining a sustainable ecosystem and drinking-water supply and that water quantity and quality are inextricably linked. The policy will take account of the natural flow within the hydrological and hydrogeological cycles when determining action which is aimed at improving or maintaining the water's good status.

The polluter pays principle will be incorporated through the use of appropriate economic instruments with which to control water usage and pollution levels, and the whole system must be managed on a river basin basis – incorporating the requirements of groundwater and surface water as an integrated whole. The policy demands forward planning, through the development and publishing of river basin management plans with a significant degree of public involvement in such processes.

20.1.1 Institutional issues for policy development

An effective first step for developing a groundwater protection policy is to establish a policy task force that draws together the key institutions with an interest in the use and management of groundwater resources. This taskforce would include e.g. Environment, Health, Agriculture, Industry, Local Government and (where there are cross-border aquifers) Foreign Affairs. Such an intersectoral task force requires representatives from senior levels of Government who are able to develop and define policy, thus it may be composed of the most senior civil servants who report directly to the Ministerial level.

A lead agency would be identified to coordinate the definition of a policy and strategy for groundwater protection and management. This agency should be mandated by the inter-ministerial body, would typically fall under a Ministry of Environment or Water, and may take the form of a Commission.

Once the institutional environment has been reviewed, rationalization can be considered as a means to develop a flexible and effective approach. This rationalization will involve identifying which organization should take lead responsibility for groundwater protection and consideration of how this should be structured, and relationships between local and national components of the organization.

Rationalization may result in the removal of responsibilities or power from some organization, which is often a difficult process. It is essential that before major changes are implemented, there is proper consideration of how this will be undertaken, what the implications will be for staff and for the organization as a whole and how this will be managed in the most effective manner.

The relationships between the organization responsible for groundwater protection and other organizations that either use or potentially pollute groundwater will need to be defined. This will include not only the Government environment, but also NGOs and the general public. The means of reporting will have to be transparent and accountable and multiple reporting mechanisms may well be required.

This institution will need to be supported by appropriate legislation and provided with adequate powers to develop and enforce regulations and laws. Such powers may include aspects such as issuing permits and abstraction licences, control of land use, defining protecting areas and establishing minimum construction requirements. The groundwater protection body must have adequate numbers of staff and resources in order to be able to monitor groundwater resources, collect essential data and ensure that they can undertake inspections and serve enforcement notices. The performance of the protection agency is highly dependent on the staff it contains and without proper training and support, it will be difficult to recruit and retain motivated staff of high calibre.

The importance of resolving institutional arrangements from the outset of developing groundwater protection should not be underestimated. Effective institutional frameworks and clear and accountable systems of responsibilities greatly facilitate achieving the objectives of groundwater protection.

20.1.2 Capacity-building to support institutional delivery

To support an intersectoral approach, interdisciplinary training is often required to ensure that staff has the necessary competence and skills to resolve groundwater issues and to work with other disciplines and sectors. Capacity-building ensures that staff is fully aware of current policies for groundwater, understand the issues related to groundwater management and have the expertise to provide advice and implement protection measures. It is also critical that they understand what other disciplines and sectors need to contribute to groundwater management. This is particularly important where water suppliers do not own groundwater catchments and activities are required by a number of sectors to ensure groundwater that is acceptable for use in drinking-water supplies (see also Chapter 16). Box 20.2 highlights an example from India where the training of staff was recognized as a critical aspect of improving institutional capacity to protect groundwater.

Box 20.2. Capacity-building in India (based on OECD, 1989)

Between 1990 and 1997, a series of training events on groundwater management was run for senior engineers and scientists aimed at improving the sustainability of drinking-water supplies. Each year, up to 18 candidates were drawn from a variety of backgrounds and locations across India. For formal training they were first sent to the United Kingdom, followed by a period of fieldwork in a selected catchment within India to observe local conditions and apply the lessons learnt to identify polluting activities as well as potential solutions. The formal training considered all aspects of groundwater development from drilling techniques to groundwater modelling and included source protection and pollution prevention modules. As the course material was developed, trainers were coached in the context and presentation of this course material to allow transfer of the training element to India. The intensive course helped promote interchange between the different disciplines and requirements and expanded understanding of the interdependence of the different work streams.

The fieldwork was undertaken over a period of five to eight weeks each year within a different State to allow a number of geological environments and levels of development to be covered. In all areas, the catchments were under stress from competing demands for limited resources or at risk from actual or threatening pollution. In the short time available the aim was for the delegates to gather sufficient information to allow an assessment of the catchment, describe the geological and hydrogeological environment, identify issues and promote solutions to aid management of the system.

The most important solution identified by the candidates was to treat the catchment as an integrated unit for both planning and management purposes. Bringing the different users and departments together was seen as a major step to sustainable development and the appropriate allocation of scarce water resources. Education of local people in both aspects of hygiene and availability of water featured highly in improving public health. It was also recognized that further training and motivation of Government staff was required, and that improvements in agricultural practices could help to conserve water and make its application more effective.

Overall groundwater availability was a major topic. Understanding its location and movement was key to successful development. The need for appropriate monitoring and sampling programmes was recognized. The provision of new, and maintenance of existing, water harvesting and retention structures to increase recharge and groundwater storage came high on the list of priorities. Often, existing structures were located in inappropriate positions or were installed for another purpose. With more integrated planning these could have been built to serve a number of purposes more effectively. Many could be modified at relatively minor costs to achieve these ends. Identification of optimum drilling locations using more modern techniques was encouraged, as in many villages some hand pumps ran dry early in the dry season due to inappropriate locations.

Recognition of the value of water and its declaration as a National Asset were also seen as important issues. This helps avoid wastage and misuse, as well as promoting better utilization of existing resources. Aspects of the ownership of water and the infrastructure to capture and distribute it were considered to be important, as were pollution prevention matters. These ranged from simple wellhead protection to management of discharges from industry. At the end of the fieldwork period, the candidates prepared and presented their findings to an invited audience of local (as well as National) government representatives, village heads, NGOs and others contacted as part of the study. They then returned to their previous posts, often to be promoted, and have used their training to encourage better communication and awareness in their local areas.

20.1.3 International groundwaters

The UN Convention on the Protection and use of Transboundary Watercourses and International Lakes, signed in Helsinki in 1992 (UN, 1992) recognizes the difficulties of protecting water bodies, including groundwaters, which cross international borders. The Convention requires all signatory countries to:

- prevent, control and reduce pollution of waters which may have a transboundary impact;
- to ensure that these waters are used with the aim of ecologically sound and rational water management;
- to use such waters in a reasonable and equitable way;
- to ensure that conservation of ecosystems is achieved.

The Convention requires the adoption of prevention, control and reduction programmes for water pollution, and the establishment of monitoring systems. Bilateral and multilateral cooperation is essential to the successful protection of such waters and riparian countries are expected to enter into agreements over such issues as joint monitoring programmes and conduct joint programmes for the prevention, control and reduction of transboundary impacts. Warning and alarm systems are required to inform countries of any critical situations that have a cross-border impact.

A Protocol on Water and Health to this Convention was agreed by an interministerial conference in London in 1999. This Protocol links the issues of human health, water resources and sustainable development and targets *'the promotion, at all appropriate levels, of human health and well-being within a framework of sustainable development, including the protection of water ecosystems and through preventing, controlling and reducing water-related diseases*'. It emphasises the need to create legal, administrative and economic frameworks to reach these targets, including the development of water management plans, and explicitly

- includes groundwater among other water environments;
- includes WHO Guidelines as translated into national and international legislation;
- addresses the protection of water used as source for drinking-water and the development of effective water management systems including controlling pollution;
- includes promoting understanding of public health aspects by those responsible for water management and vice versa promoting the understanding of basic principles of water management, supply and sanitation among those responsible for public health;
- requires the development of effective networks to monitor and assess water-related services (WHO and UNECE, 2001).

The Protocol also explicitly includes a number of principles, including the precautionary principle, particularly towards preventing outbreaks and incidents of water-related diseases, using water resources in such a way that the needs of future generations are not compromised, the polluter pays principle and access to information.

UNECE has issued further guidance concerning groundwater management (UNECE, 2000). The development and implementation of cross-border policies for groundwater depends upon institutional aspects, which include the arrangements and responsibilities for cooperation. The convention requires that socioeconomic conditions in riparian countries should be taken into account in deciding upon institutional arrangements.

As discussed in Section II, to support management of transboundary groundwaters, it is often useful that action plans, which include quantified targets and arrangements for mutual assistance, are drawn up by riparian states taking into account items such as:

- land and groundwater uses, including the possibility that restrictions or bans on certain activities may be imposed;
- zoning criteria, including the concept of protection zones;
- economic activities, paying attention to their impact on groundwater;
- pollution and abstraction of groundwater, to include the necessity of monitoring and the sustainability of abstractions.

To deal with transboundary groundwaters, the Convention requires the establishment of Joint Bodies to take on the task of monitoring and assessment of the effectiveness of the agreed measures as shown in the Box 20.3.

Box 20.3. Tasks of Joint Bodies (based on UNECE, 2000)

- Collect, compile and evaluate data to identify pollution sources;
- develop joint monitoring programmes;
- draw up inventories and exchange information;
- establish emission limits for waste water and evaluate effectiveness of controls;
- elaborate joint water quality objectives and criteria for preventing, controlling and reducing cross boundary impacts;
- develop action programmes for pollution reduction from point and diffuse sources;
- establish early warning systems;
- serve as a forum for exchange of information;
- promote cooperation and exchange of information on BAT;
- participate in EIAs;
- coordinate activities of others.

The Merske Brook Case Study: An example of international cooperation

An example of the problems relating to international groundwater bodies and steps taken to overcome these is found in the Merske catchment area of which 3185 ha are located in Belgium and 2792 ha in the Netherlands. The Merske Brook is fed by deep groundwater and infiltration from an agricultural area. The regional groundwater flow is from Belgium into the Netherlands, but there are separate local systems where groundwater from Belgium flows into the Netherlands over longer timescales. The catchment can be subdivided into an area of deep groundwater exfiltration in the brook valley, a strongly dehydrating area on which agriculture is practiced and a high infiltration area used for forestry and agriculture. Deteriorating water quality and lowering of water tables represent the problems. In order to help in resolving these problems, cross-border catchment area committees have been established with the aim of bringing about a cross-border water policy. Known as 'Markcomite' the Merske Committee was established in 1994 and has set up a number of research projects to aid water improvements. However, the problems of setting up and running such cooperation should not be underestimated. In this example it was found that clear differences existed between the two countries in their internal water management regimes which needed to be resolved. Belgium manages its groundwater at national level, whereas the Netherlands utilizes three levels – national, provincial and local water board levels. In terms of water management the Netherlands had various measurement networks already installed, supplying data to all its administrative levels, whereas in Belgium there were fewer measurement systems. However, the Dutch data were not generally mutually compatible. The availability of data was not consistent, some being digital others not. Tackling differences in institutional structures and data organization is frequently among the first tasks of transboundary water committees and major harmonization of surveillance programmes may be an important step of their work.

20.2 LEGISLATIVE FRAMEWORK FOR GROUNDWATER PROTECTION

The availability of appropriate instruments to enable the implementation of groundwater protection policies is essential. The important issue of groundwater ownership must be dealt with and revisions to water rights may be an initial stage in the implementation of policies.

20.2.1 Environmental legislation

The risk of groundwater pollution from commercial or industrial activities or urban development can be reduced through incorporating groundwater protection strategies in environmental legislation (Patrick *et al.*, 1987). Equally, individual development proposals can be assessed either through a formal EIA process and/or by systems of licensing. Both EIAs and licensing can help ensure that potentially polluting activities are located in areas where the risk of groundwater pollution is minimal. Licensing can also ensure that activities conform to best management practices (BMPs). BMPs generally define a set of standard operating procedures and design standards for a particular land use to ensure that the risk of pollution from accidental spillage or over-application and misuse of chemicals is minimized. Environmental licensing may also prescribe ongoing groundwater monitoring and may require industries to undertake groundwater remediation. Such measures need to be accompanied by enforcement with meaningful penalties, which has proven successful in many countries.

Environmental legislation can also help manage pollution from past land uses. Many jurisdictions have provisions for surveying and managing contaminated sites. Information on contaminated sites is maintained in publicly accessible databases, for example various databases have been established by the US EPA. Owners of contaminated sites in the USA (irrespective of whether they were the polluter or not) are usually required to clean up contaminated soil and groundwater before land is sold and redeveloped.

Some jurisdictions have closely aligned environmental and planning legislation in two important ways. Some environmental legislation allows entire planning schemes to be subject to EIA, and there are formal links between different pieces of legislation to allow this to happen. It is also possible in some jurisdictions to create regional environmental protection policies that can support groundwater quality and thus drinking-water quality protection. These policies will generally set out beneficial uses to be protected and protection objectives, one of which may be protecting groundwater as drinking-water resource. Such planning schemes may establish water quality standards and set prescriptive controls on land uses.

20.2.2 Legislative reform

In many countries, much of the existing planning and environmental protection legislation was drawn up before groundwater protection was a significant issue. In some jurisdictions management of groundwater pollution has been compromised because there were many government agencies with overlapping responsibilities whose decisions about particular development proposals were poorly coordinated. The management of groundwater quality issues has been improved by either reforming the way that government agencies work together using existing legislation, or by reforming legislation and restructuring government agencies. The New Zealand Resource Management Act (1991) is a good example of a piece of legislation where planning, environmental and natural resource management issues are all coordinated through a single piece of legislation.

Legislative reform alone may not improve groundwater quality protection unless there is the political will to effectively implement it (Foster *et al.*, 1992). For political action to occur, for example attaining strong support for allocating more finance to groundwater protection measures, will require that the public perceives the benefits. This poses special problems for groundwater. Frequently, the benefits of groundwater protection measures are not obvious until well into the future, whereas any controls may affect some people immediately. Communities may be tempted to postpone protection measures until the degradation of groundwater quality used for drinking-water supply becomes so severe that widespread concern amongst the general public or specific interest groups prompts them into action. However, postponing groundwater protection measures often leads to more costly and intractable problems in the long run. Educating the general community about the importance of groundwater protection is one of the most effective ways of influencing the political process to implement protection measures.

20.2.3 The law relating to groundwater ownership and abstraction rights

A fundamental legal issue, which invariably needs attention, is the question of ownership of underground water. This is because the introduction of protection measures by the State usually involves the enactment of controls that apply to groundwater or to activities on the ground above the aquifer. These controls may infringe existing rights and customs and it may be necessary to modify or withdraw the existing rights of individuals in order to enact the necessary changes. Ownership varies from country to country. In many countries common law recognizes a link between water and land ownership (Howarth, 1992), however, in others ownership of water resources lies with the State.

Where there is a link between land ownership and water, rights typically relate to the right to abstract and use water, including drinking-water abstraction, rather than rights of ownership of the water itself. In order to allow full control through a planned protection regime it is often necessary to alter the legal status of such water rights. Where plans are being developed to use water resources to their full extent, for example by the conjunctive use of surface and groundwater, existing restrictions on the general availability of groundwater caused by the imposition of individual water rights may be unacceptable. Such rights may have to be extinguished so that access to all the available water in a territory is guaranteed.

Abstraction rates may have a fundamental influence on water quality. The control of abstraction, often seen as a matter of the protection of quantity, is also an important issue relating to quality (see Chapters 8 and 19). Control of abstraction requires a sound legal basis and good enforcement. The different legal systems in different countries are very varied, but for all approaches it is essential that the law is clear as to whom regulations apply.

As a general worldwide trend, there is a realization that individual rights need to be subordinate to the protection of quantity and quality of groundwater resources, and 'rights' are being cancelled in favour of 'permissions' to undertake activities such as the abstraction and use of groundwater.

In the United Kingdom for example, where there are no established rights to riparian ownership of underground water, but there are long-standing common law rights for its abstraction and use, Section 24 of the Water Resources Act 1991 requires abstractors to obtain a licence from the EA to drill a borehole and abstract underground water. Once granted, this gives an indefinite right to withdraw water. The use of the water may be specified as for drinking, irrigation, and so forth. However, under new proposals to ensure the long-term sustainability of aquifers, these rights will be modified by central government and time limits will be placed on the permit. The government originally proposed a limit of 15 years when new authorizations are granted but, following extensive consultation, the time limit may be varied to reflect an individual catchment situation depending upon the local availability of water.

Time limits on licences to abstract are imposed in some other countries. In South Africa, individual ownership has been extinguished by decree under the Water Act (1998), which takes the view that underground water is a common resource. Whilst individual ownership rights to water are withdrawn, rights to abstract and use water are granted through a licensing procedure. Licences are issued on a five-year cycle and for a maximum time of 40 years, determined by the use to which the water is put. A reserved quantity of 25 litres per person per day is retained before other uses are authorized to ensure that people have access to sufficient water.

In Arizona, a dry state of the USA, Active Management Areas are established where groundwater is under threat. The use of groundwater is generally subjected only to rules on reasonable usage, but where it is in short supply, water management rules are applied and new abstractions of groundwater are subjected to a permitting procedure.

20.3 CONSULTATION AND PARTICIPATION

The general public can only participate in decision-making on environmental health issues if it has access to information. Often what is needed first in programmes to protect groundwater is to ensure that all staff has the understanding and the tools to establish a dialogue and atmosphere of trust with stakeholders. A Canadian expert on participation has stated:

> *'The level and quality of participation by the public will be no better than that of the staff in the proponent's organization… The development of a relevant public participation policy is often part of the pre-work needed before launching a pro-active program with the organization's external publics.*' (O'Connor, 1993).

The general manager of the Montgomery, Alabama, Waterworks, emphasizes the point of ensuring all staff know how to listen:

> *'A key aspect of our program involved sitting back, getting out of the driver's seat and becoming a one-vote stakeholder during the decision process, even though our agency was providing funding for the program… All of this inspired openness, trust and full buy-in among the 25 different stakeholder groups involved in the Catoma Creek Watershed.'* (Water and Wastewater International, 1999).

Understanding the needs of the community, whether it be an entire nation or a small village, is a prerequisite and part of the process of establishing a dialogue. Professionals in public and private agencies developing policies must understand what the public wants from them and be clear about what they want from the public. From that knowledge, they can then begin to develop mutual trust, common goals and plans. This requires that the breadth of views are represented. Continuous information gathering, and reconfirmation with the stakeholders of conclusions on knowledge, attitudes and practice is important for ensuring accuracy of assessments, monitoring of progress and change, and establishing trust among stakeholders. Transparency of information dissemination is extremely important and requires the development of communication plans. In Bangladesh for example, communities had limited information with which to make decisions, and it was recognized that improving their access to information would strengthen their ability to fight for their rights (see Box 20.4).

Box 20.4. Bangladesh – community initiative in regulating industrial pollution

A detailed study of various publicly owned fertilizer and pulp plants showed that *'even very poor people in Bangladesh can negotiate pollution reduction and compensation when the damage is evident and they have economic alternatives.'* The survey revealed *'a pattern of informal regulation which has remarkably similar characteristics. Fish kills, paddy crop damage and poisoned drinking-water provide a straightforward, but limited, basis for damage estimation by downstream communities. Plant staff members live and work near these communities, and are therefore potentially subject to social pressures ranging from harassment through ostracism to outright violence.'* However, community pressure was only effective in areas where community members had alternative employment. In addition, *'the affected communities are hampered by poor information. In some cases they cannot identify the offending polluter; they have little basis for assessing pollutant risk; and they generally know little about the cleanup options faced by polluting firms.'* In these cases, the communities need outside help from an NGO, government agency or concerned business in order to obtain more accurate information to support their claims (Huq and Wheeler, 1993).

Similarly, a fundamental tenet of integrated water cycle management (including all waters) that is being developed in NSW, Australia is the inclusion of all identified stakeholders at the outset of the process. Agency staff develop and disseminate information initially with the local water utility and then with the government agencies and local interest groups. This process has ensured ownership of the process by all involved as it is possible for everyone to understand how they impact on the water cycle. Information is then used to refine the process and the adopted control measures that are decided on by the local water utility and the community it serves.

Community participation is an ongoing process of information gathering, dialogue and negotiation. In the United Kingdom for example, where water and wastewater services have been privatized, this was accompanied by creating the Ofwat National Customer Council and Service Committees. Their mandate is to ensure that companies continue to supply good quality drinking-water, look after the environment, keep average prices low, improve customer service, and particularly to ensure this dialogue between customers and providers (OFWAT, 1998).

In developing countries, community participation in the provision of water supplies and sanitation has been shown to be effective in rural areas and is increasingly noted as successful in urban areas (World Bank, 1993; IRC, 1995; Satterthwaite, 1997; WHO and UNICEF, 2000). Community participation in water resource management has been less widely applied but is increasingly noted as successful, particularly within local communities. Experience is far more limited with processes of dialogue with communities about national and international water resource management despite the urgent need in many parts of the world to ensure that this occurs.

Cultural values of groundwater

In some countries, groundwater has specific cultural meanings for part or all of the population. It is important that these values are included in public participation programmes on groundwater quality issues involving and/or affecting indigenous communities. Some of these concepts are illustrated below with the example of participation programmes involving aboriginal communities in Western Australia.

Under Western Australian Aboriginal Heritage legislation, it is an offence to disturb sites of special cultural significance to aboriginal communities, which generally include land near springs, groundwater-dependent wetlands and waterways. It is a requirement for all major development proposals to ensure that adequate consultation has taken place with relevant aboriginal communities, including local custodians who are able to ‘speak for the land’. Consultation has to take place in a culturally sensitive manner and is usually mediated by anthropologists.

In developments that utilize large amounts of groundwater and can cause groundwater contamination such as large irrigation projects, it is important that aboriginal communities are involved at an early stage in the planning stage to ensure the protection of cultural values (Macintyre and Dobson, 1998; Yu, 1999). Allocation plans for groundwater resources can then be developed ensuring that sufficient water is allocated for the maintenance of cultural and environmental values before divertible resources are determined. Cultural values (often the maintenance of specific water levels in wetlands) have to be determined by consultation with relevant communities, and sufficient research and site-specific investigations have to be undertaken to convince these communities that groundwater quality will not be affected by the development (Yu, 1999).

Consultation is also needed when assessing and remediating existing groundwater problems. One example is the metropolitan region of Perth, the largest urban centre in Western Australia with a population of 1.3 million. There are a large number of heritage sites in this area, particularly near rivers and wetlands. Consultation is required to ensure that the location of monitoring boreholes to assess groundwater contamination and that remediation using in-ground structures will not disturb sites of cultural importance.

20.4 LAND USE PLANNING AND MANAGEMENT

There is a long recognized relationship between land use and pollution of groundwater, although this may take decades to be noticed. Once pollution of an aquifer has occurred, it is extremely difficult to clean up and it is rarely possible to return an aquifer to a pristine condition. For this reason, the best practice is prevention through the regulation of land use in areas that overlie groundwater flow systems.

This section discusses both the advantages and the limitations of land use management for protecting groundwater resources and provides an introduction to the mechanisms and approaches commonly used to control land use. Land use management to protect groundwater quality usually involves a combination of approaches and the particular mix used will vary considerably.

20.4.1 Regulatory approaches to controlling land use in sensitive areas

Land uses and economic activities in sensitive areas, particularly in drinking-water catchments, need to be subject to some form of government regulatory control, and require approvals to proceed. Land use can be managed through a variety of tools including national or regional planning regulations, environmental legislation and local government by-laws.

Although planning legislation varies considerably from country to country, it is commonly organized in a hierarchical manner. Broad policies and principles are set at the national level (or at an international level, where there is international grouping, such as the European Union). Local regulations are established at a state or regional government level, and local government is responsible for town planning and regulating local zoning and the subdivision of land. Most planning controls to protect groundwater quality are implemented by local governments, but groundwater protection issues can be incorporated into national planning policies and regional planning regulations, as they are in many states in the USA. The Statement of Planning Policy for the Jandakot region in Perth, Western Australia shown in Box 20.5, provides an example of a regional policy that recognizes the importance of groundwater protection.

Controls on land zoning and subdivision imposed by local governments can be very effective tools for protecting groundwater. Zoning consists in dividing a locality into areas where the allowed land uses are specified and can be used both to define the kind of land uses permitted and to regulate the permitted uses. Zoning can be used, therefore, to direct future development towards defined objectives (groundwater protection usually being only one of many reasons for controlling land use). Typical zoning requirements for groundwater protection generally limit permitted uses, for example to low density residential development with limited use of septic systems, or leaving land as public open space. Such controls require continued monitoring to ensure that the requirements are maintained through time. The protection zone concept for drinking-water catchments is discussed in more detail in Chapter 17.

Box 20.5. The Jandakot regional groundwater protection regulations (based on Boyd *et al.,* 1999)

The protection of groundwater quality is recognized as an important element in land use management in the Perth Metropolitan Region Scheme, the planning framework for the city of Perth. The Jandakot mound is one of the recharge areas for the region and includes land currently reserved for the protection of groundwater quality. Here, the purpose of the regional policy is to:ensure: that development in the area is compatible with the long-term use of groundwater for public water supply and ecosystem maintenance; ensure that land uses with potential detrimental effects on groundwater resources are brought under planning control; provide guidance on planning requirements for development proposals; guide local governments in amending their town planning schemes; acquaint affected landholders with the proposed changes in planning controls.

Regional plans like that for Perth can help protect groundwater by ensuring the appropriate location and density of specific types of development, and by ensuring that waste disposal sites are located appropriately. Regional plans can also help guard against inconsistent decisions being made at a local government level when individual development proposals are viewed in isolation.

Controls on land zoning and subdivision imposed by local governments can be very effective tools for protecting groundwater. Zoning consists of dividing a locality into areas where the allowed land uses are specified and can be used both to define the kind of land uses permitted and to regulate the permitted uses. Zoning can be used, therefore, to direct future development towards defined objectives (groundwater protection usually being only one of many reasons for controlling land use). Typical zoning requirements for groundwater protection generally limit permitted uses, for example to low density residential development with limited use of septic systems, or leaving land as public open space. Such controls require continued monitoring to ensure that the requirements are maintained through time. The protection zone concept for drinking-water catchments is discussed in more detail in Chapter 17.

Where they are successfully applied both zoning and subdivision regulations are most useful for controlling future development. However, they have little effect for groundwater protection purposes in areas with previous development that led to pollution. Some countries do, however, use such methods to control further degradation of protected areas. For example, Chilean environmental legislation includes the concept of saturated zones where no further development is permitted when one or more environmental standards have already been surpassed (Government of Chile, 1994). In Perth, Australia, there are programmes to replace septic tanks with sewer connections, but existing groundwater contamination will take many years to dissipate. There are also media campaigns promoting the wise use of water and fertilizer, and of the benefits of using local native plants in gardens, which do not need fertilizer (Appleyard and Powell, 1999). A number of community action groups are also becoming interested in the issue.

20.4.2 Other land use measures for pollution control

Governments are often reluctant to impose new controls and regulations on existing activities to or impose retrospective legislation because of the potential for economic disruption. Other forms of intervention are often required to protect groundwater quality, usually taking the form of financial incentives or penalties.

In particularly sensitive areas, governments may decide to purchase activities considered to be potential sources of pollution, or offer significant financial incentives for industries to relocate. Practices that cause groundwater pollution may be given incentives for change. For example, tax incentives to use a specific type of fertilizer or pesticide that is less susceptible to leaching or degrades in the soil more quickly, can be an effective tool. Imposing penalties for any pollution above a certain standard also has a role to play.

Market based approaches seek to relate the cost of contamination to the cause so that the price mechanism can be used to restrict the amount of contamination that reaches groundwater. Stringent application of the polluter pays principle should also lead to polluting activities paying for the monitoring and reporting of contamination levels in groundwater. Other market mechanisms such as insurance bonds may provide added incentives for avoiding the pollution of groundwater in the longer term.

20.5 TOOLS FOR POLLUTION CONTROL

There are a number of specific tools and incentives that may be employed to maximize the impact on groundwater protection policies and regulations. This may include the setting of specific end-of-pipe control, establishing integrated pollution control measures, use of prohibitions and the use of codes of practice. Some of the tools are discussed more specifically in Chapters 21-25. Water quality objectives may also be determined to provide a mechanism to reduce pollution of groundwater.

Within all these approaches, the use of incentives is often as effective as the use of prohibitions or controls. By providing evidence of benefits derived from reduced pollution, many industries will be interested in changing practices. However, the use of regulations remains important, but will only be as effective as the degree to which these are enforced. Regulations and standards, without the back-up of inspection and enforcement regimes are largely worthless. Similarly, regulations that are applied discriminately may send the wrong message. For instance, towns and sewage services are seen as an easy target for regulators when in fact it is often the agricultural sector that is the major polluter. In some countries, the agricultural sector may be politically powerful and may seem to be immune from regulatory enforcement in part because of difficulties in enforcing regulations relating to diffuse sources. Tools for pollution control thus need to be equitable and uniformly enforced.

Legislation developed for general environmental protection and pollution control can be employed to deal with activities which affect the quality of groundwater used as drinking-water source. For example, laws which are used to regulate the quality of discharges to watercourses so that the quality of water is not impaired can be extended to groundwater. Permitting procedures for the discharge of materials from factories and wastewater treatment plants are commonly used to control point source pollution and these procedures can be applied specifically to protect groundwater. Control measures for diffuse sources of pollution are more difficult to implement but the use of land use planning procedures, codes of practice, and general attention to the pollution risks from activities may help to reduce the risks of groundwater pollution. Pollution from road construction, quarrying, landfill and oil installations, for example, can be tackled by agreeing to necessary precautionary measures with the developers and operators of the systems. Agricultural policies can also be developed that control the release of pollutants, through for instance control of fertilizer and pesticide applications, as noted in Chapter 21.

20.5.1 End of pipe controls

Legal remedies to groundwater pollution from point sources generally operate in one of two ways – control of the discharge or control of the process from which the discharge originates. In situations where it is possible to identify a discrete discharge from a pipe or other such structure a ‘permitting’ regime may be established to control discharges of polluting materials into watercourses or into the ground. In other cases, point source pollution (for instance from pit latrines) may be controlled in sensitive areas by establishing specific design and construction criteria.

It may be considered necessary for an industrial or commercial organization to dispose of its liquid effluents into or over the ground above an aquifer. In such cases the permitting system may give adequate control over the quantity and content of the effluent so that the groundwater is protected. Commonly used as end-of-pipe controls, such permits are issued under legislation by the pollution control authorities following an application for permission to discharge. The law usually requires an application to be made by the discharger, stating the likely rate and constituents of the discharge, and the authorizing body must take steps to consult interested parties and examine the likely effect on the water before the permit is granted.

In the United Kingdom for example, Section 85 of the Water Resources Act 1991 makes it an offence to allow the entry of poisonous, noxious or polluting material into controlled waters (that is, most naturally occurring surface and underground waters), but a discharge may be made following the issue of a permit under Section 88 of the Act. A permit is granted after receipt of an application, local and national advertising of the proposal, consultation with affected persons and statutory bodies and after consideration of the likely effects of the discharge on the relevant water. A permit so granted may place strict limits on the constituents of any discharge and the manner in which it is discharged to prevent any deterioration in the receiving water.

If the effluent contains particularly toxic or dangerous substances the issue of a permit may have to be refused, as the risk of contaminating the groundwater to such an extent that it could not be used for drinking purposes would be too high. This situation has been dealt with in the European Union through the adoption of a specific directive, the

Groundwater Directive (80/68/EEC) (EU, 1980), which prohibits the direct discharge of dangerous substances into these waters, requires permits for indirect discharges (i.e. discharges which percolate through the unsaturated zones), and which also limits the discharge of other substances which may lead to pollution. This directive is reflected in the local legislation in each of the Member States through a process of legal transposition.

20.5.2 Integrated pollution control approach for industry

Although the use of permitting is an effective way of controlling known effluent discharges, groundwater is easily contaminated by other routes. There are many examples where spillage of materials or poorly designed storage facilities at industrial sites (Chapter 11) have caused pollution and the careful control of discharge points has not given adequate protection from activities on the site. Such problems extend to the pollution caused by the disposal of solid wastes. To overcome such lack of control of potentially polluting activities an alternative approach has been developed (see also Chapter 23). In this concept, rather than limiting legislative control to the permitting of individual discharges, the overall process itself is the subject of a permitting regime. The approach uses the principle that all possible environmental impacts of all activities on the site should be considered, taking account of the effects of the installation and its discharges to air, land and water. Prior authorization must be obtained before the installation is allowed to operate, and where a permit is granted and there are discharges to the environment, the principle of using the best available techniques is applied to prevent or minimize the extent of the discharges. This system has now been adopted in the European Union, for example, through the Integrated Pollution Prevention and Control Directive (EU, 1996).

Experience of using this manner of control has been gained in a number of countries. For example, in the United Kingdom the Environmental Protection Act 1990 introduced Integrated Pollution Control to a specified range of the most polluting industries; in France the Law on Classified Installations of 19 July 1976 defines discharge thresholds for air and water and the technical conditions which must be fulfilled in order to be granted permission to undertake the activity; and in Sweden the Environmental Protection Act of 1969 covers emissions to air and water and noise emissions and is based on integrated pollution prevention principles. At present this regime is used for larger installations because of the amount of work involved in assessing the pollution potential and in enforcing the conditions of the resulting rather complex permit, but the principle is capable of adoption for any size or type of plant, and could be used to limit the construction of undesirable installations where groundwater is particularly at risk.

Such an approach is particularly valuable for groundwater protection because the procedure of assessing the impact of the process on the environment enables the identification of risks of pollution from diffuse inputs as a result of spillages from storage facilities or operations within the plant and also allows an assessment of the impact on groundwater of such activities as ground disturbance during construction. The approach requires attention to be given to the possible risks from closure of the site and any clean-up measures required at this stage. This approach has central principles in common with the WSP approach (see Chapter 16), such as system assessment for identifying risks and process control. It is therefore a good basis for developing a WSP to include aquifer protection.

20.5.3 Prohibitions

In some cases it is not possible to provide adequate protection of groundwater by means of a permitting regime. This is because either the activity is regarded as too unpredictable to enable enforceable conditions to be added to the permit, or because the activities are intrinsically too dangerous to public health to permit them to be carried out in an area used for water supply. In such cases the use of a prohibition notice may be required. The legal basis of this must be clear, however, and the law needs to be clear on precisely what is prohibited, and there must be suitable penalties to encourage people to obey the prohibitions together with adequate enforcement.

Some countries use prohibitions as a precursor to the issue of a permit, so that the legal position is that the activity is prohibited unless a permit is in force, or unless specific standards are met. For example, the Nigerian National Environmental Protection Act of 1991 prohibits the release of hazardous or toxic substances into the air, water or land unless limits set by the national Agency are met.

In the United Kingdom prohibition notices may be issued at any time by virtue of the Environment Act 1995 in respect of activities that are considered likely to cause pollution. Such notices are short-term prohibitions requiring the person on whom they are served to take action to deal with a problem.

20.5.4 Prevention of diffuse pollution of groundwater through Codes of Practice

In some cases, the issue of specific legal direction to avoid pollution is not possible. This is particularly the case for non-point source pollution. For example, it would be very difficult to control agricultural activities (Chapter 21), any of which might cause contamination of groundwater, by the issue of laws covering all the possible activities involved. In such cases the issue of codes of good practice offer an alternative. However, approaches may be developed to consider the point of drainage of a sub-catchment into other catchments, in which case the point of drainage can be seen as the point source. Under this approach, targets may be set for sub-catchments and the activities within that sub-catchment regulated or required to operate within BMPs accordingly.

In the United Kingdom a Code of Good Agricultural Practice has been issued (MAFF, 1991), and this has been given statutory status which means that if a farmer causes pollution and is taken to court, the question of whether or not he has obeyed the Code may be used as a material fact when deciding upon his penalty.

Codes of Practice can be devised and successfully operate in a wide variety of situations which could affect groundwater quality and quantity, including such diverse areas as road building, mineral excavation, fuel storage and use and many more. The codes should identify best practice in the context of the prevention of groundwater pollution. This is an important commercial reality for water suppliers since guidelines, BMPs and codes of practice generally represent the current accepted body of knowledge of their profession, making their application essential to demonstrate all reasonable precautions and due diligence (Davison *et al.,* 1999).

20.5.5 Prevention of diffuse pollution of groundwater through regulations

Although many activities are difficult to control through a legal permitting regime, it is possible to identify some situations in which it is possible to be more precise about the methods used to control them and to issue legally binding regulations or decrees. These usually apply to particularly discrete issues. For example the problem of slurry storage and slurry use on farms is a major problem to groundwater quality but the problems and their solution can be readily identified. They relate to the design and use of storage facilities, and how and when farm slurry can safely be spread on land in such a way that water pollution is avoided. The Control of Pollution (Silage, Slurry and Agricultural Fuel Oil Regulations) 1991 of the United Kingdom is an example of a legally binding regulation that sets out detailed guidance on storage and usage requirements. Such a regulation would also have to be obeyed if the farmer was abiding by the Code of Good Agricultural Practice but is a legally binding obligation in its own right. Similar issues for which governments implement such regulations include specific requirements for the storage and transport of hazardous chemicals or for car-washing facilities (see Chapters 23 and 25).

20.5.6 Water quality objectives

It is also possible to establish statutory water quality objectives for the water body, with the compliance of such objectives a legal obligation. Water quality objectives define a quality of water that must be met continuously for the whole water body taking into account the range of needs (suitability for water supply, irrigation, industry and ecological needs). Permits for waste discharge and disposal are then issued on the basis of whether the discharge will cause deterioration in water quality so that the objectives are no longer met. The advantage of setting such objectives is that it allows an overall framework for water quality management across the water body and places individual controls within a broader framework. Thus the nature of individual discharge permits within water quality objectives requires that not only the impact on the immediate area is considered, but also wider impacts on the water body as a whole.

In the groundwater context applying such objectives may be more problematic, as the effect of individual discharges on the mass of groundwater in an aquifer is very difficult to predict and the proportion of the total amount of a contaminant found in an aquifer that can be reasonably allocated to individual polluters is often difficult. The use of statutory water quality objectives is therefore little used for groundwater, although the new Water Framework directive of the EU proposes to establish objectives related to groundwater status, including quality and quantity.

20.5.7 Controls on product specifications

For some pollutants, for instance pesticides, controls on production and use may be effective in reducing the risk of groundwater contamination.

This approach is being taken in a number of cases. In Canada, for example the Pest Control Products Act 2002 regulates the distribution of those pesticides which are likely to influence groundwater quality in a non-specific way, and the Pest Management Regulatory System controls the production of pesticides. Such a system, although remote from the point of influence, is believed to provide a holistic preventative measure against groundwater pollution from pesticides. A rather similar indirect control on pesticides has been introduced in the EU through the so-called Uniform Principles Directive (91/414/EEC) in which a uniform authorization process is used to approve the active ingredients in pesticide formulations before they are placed on the market.

20.6 ENFORCEMENT

The value of regulations is dependent on the degree to which they are enforced. An essential prerequisite for groundwater protection regulation, therefore, is that the organization responsible for protecting groundwater has a clear legal mandate, including the powers to take action against organizations or individuals who breach the regulations. This applies whether this organization operates at a national or local level and whether groundwater is dealt with on a catchment, region or whole country basis.

Once the legal basis on which groundwaters are to be protected has been established and the policy has been implemented, there must be means of ensuring that those affected continue to comply with the provisions. The regulatory organization needs to be granted powers to inspect and to take action against non-compliance. The organization may be the same as that which grants permits or controls pollution. Alternatively it can be a separate enforcement agency or, as in some countries (e.g. Italy), it could be a branch of the civil police. The organization will require legal powers to:

- enter property and land
- inspect and collect data
- prosecute or levy fines.

A key issue to be resolved is the determination of what constitutes a breach of compliance of the legal requirements. The enforcement agency has a duty to determine whether this has occurred. A decision must be taken as to when such a breach warrants enforcement action, and the agency requires legal powers to proceed. Legal powers may consist of verbal or written warnings, formal notices, administrative acts and fines, invoking criminal sanctions. In some cases civil law may be used against a polluter. The enforcement regime should contain a practical mechanism for ensuring that compliance is improved. Enforcement is itself part of a cycle as shown in Figure 20.3.

Permits and licences have to be drawn up in such a way that their conditions are achievable. Compliance control of discharges and abstraction must be enacted by suitable protocols, inspection visits, sampling, and other means of verification. An important aspect of enforcement is promotion of the concept that licence holders should take responsibility for meeting their conditions. The need to use enforcement action through the courts or by other means should be a last resort. The possible need to review and change legislation as a result of experience is also an integral part of this cycle.

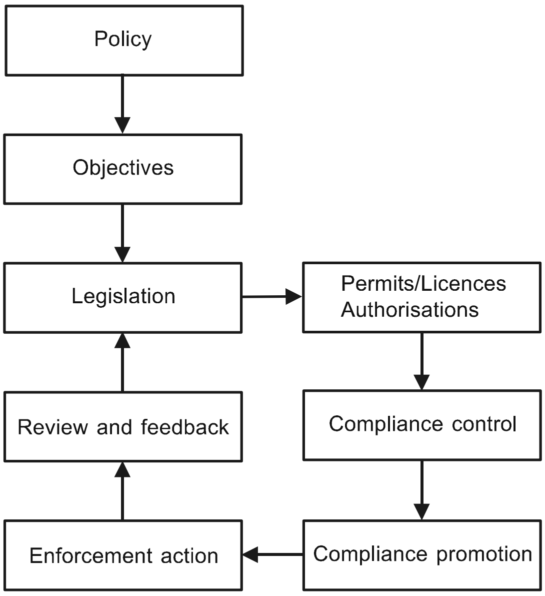

Figure 20.3. Regulatory cycle (adapted from Glaser, 1996)

20.7 MANAGEMENT PLANS FOR DISASTERS AND INCIDENTS

Disasters and major incidents affect all countries and the development of management and preparedness plans for such situations is important in protecting public health. Extreme conditions often place both the use and the management of groundwater under considerable stress, as the quality and quantity of water from groundwater sources may be affected. They may also become more important in the supply of water during disasters as other sources become heavily contaminated and therefore good management of groundwater where it is used for drinking purposes is essential. It is important to develop intersectoral plans to protect groundwater during these events and to ensure that different institutions have clearly defined roles and understand their responsibilities in responding to disasters.

The management challenges in extreme conditions will vary depending on the nature and extent (both spatial and temporal) of the condition, local factors, available resources and available information about appropriate technologies. Without the development of management plans that can be quickly and effectively implemented, extreme events may cause great suffering to the affected populations and may compromise the viability of groundwater resources in the longer term.

Disasters can be natural, including geological (earthquakes, volcanic eruptions, landslides, tsunamis) and meteorological (tropical cyclones, floods, droughts), or man-made (social disruption, war, industrial accidents, ecological mismanagement). Globally, tropical cyclones, floods and earthquakes are shown to be the most frequent types of disasters with earthquakes and tropical cyclones the most deadly regarding human life.

The severity of a disaster depends on the magnitude of the event and the vulnerability of the population and infrastructure. The people affected by a disaster are often faced by increasing health risks and are often more vulnerable to water related diseases. For instance, post-disaster diarrhoea epidemics frequently occur due to lack of access to safe and adequate volume of domestic water. The causes of this reduced access are varied and include damage to shallow groundwater sources and pollution of shallow aquifers. The consequences of poor preparedness may be very significant for public health as shown in Box 20.6.

Good disaster preparedness and mitigation plans have important implications for groundwater protection and health. Ensuring that appropriate measures are put in place to reduce the likelihood of large-scale disruption or pollution of supply and developing rapid response plans – for instance emergency chlorination programmes – will reduce the impact of the disaster on water supply and public health.

Controlling widespread contamination of the shallow aquifer may not be easy. However, remediation is sometimes not as difficult as assumed. For instance in Bangladesh it was found that the quality of water from flooded hand pumps usually became better after it is pumped over several hours.

Disaster preparedness

Effective disaster preparedness involves a range of stakeholders, including Government departments responsible for health, social services, water and local Government as well as communities, the private sector and NGOs. It is usually most effective when a lead agency is identified that takes responsibility for coordinating and planning the emergency response and for ensuring that different agencies are aware of the support available and the different roles they are expected to play.

Emergency actions are usually looked upon as being short-term measures. However, proper disaster management has immediate to long-term implications for appropriate protection, utilization and sustainable development of the groundwater resources. A properly developed disaster preparedness programme is an essential first step in this management.

The prorgramme should begin with a survey and mapping of all water facilities. It may be of value to utilize GIS as a means of storing and presenting data in order to define vulnerable areas and priority interventions. This will allow proper planning for the disaster response to be undertaken and should indicate special needs for groundwater protection and identification of points where resources must be available.

Based on field surveys and assessed needs, the activities and procurement of the materials possible within the available resources should be managed in consultation with the stakeholders. Proper utilization of the disaster information and warning centres should be part of the groundwater protection preparedness initiatives. Attempts should be made to integrate the preparedness and response to disaster into the national planning and policy framework. Developing a strategy for community awareness-raising is essential to support disaster preparedness.

Box 20.6. Flooding and groundwater contamination in Bangladesh after cyclones

During the cyclones in 1991 and flood in 1998 in Bangladesh, many tubewells were damaged and remained under water over several days and this led to deterioration in the physiochemical and microbial quality of the water. This probably occurred due both to direct ingress at the tubewells themselves as a result of inundation and a much wider gross contamination of the shallow aquifer. As the majority of the Bangladeshi population drinks water from tubewells, the damage and contamination of the tubewells represented a major public health crisis (Siddique *et al.,* 1991). The numbers of people using the non-flooded tubewells increased significantly leading to long queues and long distances to tubewells. The reduced access to safe/usable tubewells affected the availability of water and consequently hindered personal and kitchen hygiene practices. As a result, diarrhoea epidemics were observed.

One of the problems that Bangladesh faced was poor preparation for the effects of such a disaster, despite the regular occurrence of such events. The limited knowledge of groundwater management meant that little protection was provided to prevent damage to the infrastructure and remediation of widespread contamination of the shallow aquifer. Water was transported from other areas to the affected areas even though the water from non-flooded handpumps was safe. This created panic and unnecessary water shortage among the local people as they abandoned the local groundwater for the transported water. Moreover, the bacteriological quality of transported water was worse than the local handpump water and therefore represented a higher risk to public health.

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21

Agriculture: Control and protection

S. Appleyard

Agricultural activities can contaminate vulnerable aquifers with a range of pathogens and hazardous substances. The scale of their groundwater pollution potential is different from other human activities, as animal manure, agrochemicals, sewage sludge or wastewater are intentionally applied to land, often to large areas. Contaminants relevant to human health include a range of pathogens carried by farm animals but also infectious to humans, nitrate and a wide range of pesticides. Land clearing and irrigation practices also impact aquifer vulnerability and hydraulic loading and thus affect pollution potential.

There are a wide range of measures that can be implemented to reduce the impacts of agricultural production on groundwater quality. These include structural measures such as the construction of treatment facilities for wastewater from intensive animal feeding operations or adequately sized, sealed and bounded sites for pesticide mixing and cleaning of equipment; and operational measures such as applying the correct amount of fertilizer at times of the year when plant uptake occurs, or matching irrigation to crop needs. Control measures in planning address the type of agricultural land use in relation to aquifer vulnerability and use. Examples include restricting or limiting stock density and type of crop. In general agricultural management practices are aimed at reducing the pollution of groundwater by either minimizing the availability of pollutants (source reduction), by retarding the transport of water, pathogens and nutrients through the soil profile, or by chemically or biologically transforming chemical pollutants (e.g. pesticides) into less toxic materials within the soil profile.

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These management practices are often referred to as good management practices. However, the term “good” is often a highly subjective and site-specific label: what is adequate in one area may not work in a different location due to differences in physical conditions, or to cultural factors which may restrict the adoption of a particular measure by local farmers.

Management practices generally cannot solve water quality problems in isolation, but are used in combinations to build management practice systems (US EPA, 2000). For example, soil testing is a good practice for nutrient management but, to be fully effective, it also requires estimates of realistic yield, good water management, appropriate planting techniques, proper nutrient selection, rates and placement. A set of practices does not constitute an effective management system unless the practices are selected and designed to function together to achieve specific water quality objectives reliably and efficiently. Their documentation in a management plan is important to define routines of monitoring whether practices are being adhered to and are functioning as intended.

In general, changes in agricultural practices will only occur if there is some incentive for new techniques to be adopted. This usually means that the measures are affordable for farmers, and that they can either see cost savings in implementing the measures, or that financial incentives are offered by government agencies, water suppliers or consumers for implementing the measures. The provision of a system of branding goods as environmentally responsible products may also be of benefit to the growing market for organic and green produce.

The implementation of good management practices and control measures to protect drinking-water catchments from contamination through agricultural activities is substantially facilitated by an agricultural policy targeting sustainable use of resources. Many measures for this broader environmental target will encompass the protection of groundwater used for drinking-water. They may include but are not restricted to:

- training and education programmes to increase local awareness of agricultural impacts on groundwater and drinking-water quality;
- establishment of catchment management groups with involvement of local community, relevant government agencies and local politicians;
- conversion programmes of arable land to unfertilized grassland.

Vice versa, the development of control measures for agriculture in drinking-water protection zones in some countries has pioneered the development of approaches to environmentally sound agricultural practices.

This chapter presents information on management practices that have proven to be effective in controlling groundwater pollution, and looks at how they can be implemented both at the farm scale and at the catchment or watershed scale. It is not intended to be a comprehensive account of all agricultural pollution control measures, but sufficient information is provided for local authorities to develop practices suited to their local conditions, usually in collaboration between the sectors responsible for public health, water management, agriculture and environment.

NOTE ▶ *In developing a Water Safety Plan (Chapter 16), system assessment would review the efficacy of control measures and management plans for protecting groundwater in the drinking-water catchment from agriculture. Chapter 9 provides the background information about the potential impact of agriculture on groundwater and provides guidance on the information needed to analyse these hazards.*

This chapter introduces options for controlling risks from agriculture. As the responsibility for agriculture usually falls outside that of drinking-water suppliers, close collaboration of the stakeholders involved, including the authorities responsible for agriculture, is important to implement, upgrade and monitor these control measures. This may be initiated by the drinking-water sector, e.g. in the context of developing a Water Safety Plan or of designating protection zones (see Chapter 17).

21.1 PATHOGEN MANAGEMENT ON AGRICULTURAL LAND

As discussed in Chapter 9, a number of pathogens occurring in animal manure may also cause illness in humans. These include bacteria (e.g. *E. coli* O157:H7, *Leptospira, Yersinia enterocolitica, Campylobacter* spp., *Listeria moncytogenes*, *Salmonella* spp., *Clostridium perfringens*), viruses (e.g. hepatitis E) and protozoa (e.g. *Cryptosporidium parvum, Giardia lamblia*). Pathogens may further be introduced through wastewater irrigation or use of sewage sludge on agricultural land. Although filtration through the subsoil may attenuate them more readily than nitrate or agrochemicals, where they do break through into drinking-water aquifers, pathogenic microorganisms are likely to present the most immediate and serious threat to public health. Consequently in such settings, implementing management measures to deal with this issue often has a high priority in relation to contamination from agrochemicals. Many of the management measures that are implemented for controlling groundwater contamination by pathogens, however, will also prevent contamination by chemicals derived from agricultural land use.

In general, there are four specific points in a farm management system where targeted control measures will help prevent the transport and proliferation of microorganisms that may be carried by stock but can cause disease in humans. These points are:

- *Avoiding the import of pathogens into farms to prevent a specific disease from becoming established and proliferating in a farm setting.* The main sources of pathogen import include new stock, the purchase of contaminated feeds, importing contaminated drinking-water, infected farm workers, contaminated soil and manure carried between farms on farm machinery or tools, and the introduction of diseases by pests and wildlife.

- *Interrupting the cycle of pathogen amplification and proliferation on a farm.* Pathogens can be circulated on a farm through poor storage and handling practices for feeds, drinking-water, and animal wastes.
- *Safe waste management.* Poor waste management practices can contribute to animal re-infection and can greatly increase the risk of groundwater becoming contaminated with pathogens. The risk of waterborne disease is particularly high in areas where fresh human excrement is applied as a fertilizer and for soil amendment.
- *Preventing pathogen export or transport from a farm.* Without careful management, pathogens can be exported from a farm to initiate a cycle of infection and drinking-water contamination in other areas.

Management measures that are effective in minimizing pathogen proliferation at one or more of these points are outlined in Table 21.1, and are described in more detail below. A more detailed overview on zoonotic waterborne pathogens in animal reservoirs and their control on farm level is given by Gannon (2004). In general, management measures to reduce pathogen levels on farms should not be implemented in isolation, but rather an integrated pathogen management system should be established where linked management measures that target one or more of these control points work together to break the infection cycle that can indirectly lead to the contamination of drinking-water.

Table 21.1. Control measures for addressing pathogen proliferation and transport on a farm (adapted from Rosen, 2000)

Measure	**Management area**			
	Import control	Proliferation of pathogens on farm	Waste management	Export control
Composting wastes		X	XXX	X
Constructed wetland			X	XXX
Filter strips				XXX
Riparian buffers				XXX
Sediment traps				XXX
Waste management system (including storage, treatment ponds, waste reuse)		XXX	XXX	
Irrigation water management				XXX
Prevent stock access to wellheads and streams by fences		XXX	XXX	XXX
Regulatory control of stock feed sales	XXX			
Quality assurance system for preparing stock feeds	XXX			
Washing farm machinery	XXX			XXX

xxx = direct control of pathogens; x = indirect control of pathogens

Although the above control measures will greatly reduce the numbers of animal-borne pathogens on a farm, it is unlikely that specific pathogens will be totally eliminated from an agricultural environment. Consequently, additional management measures are generally required to protect groundwater supplies from microbial contamination in agricultural areas to prevent the spread of waterborne diseases. Measures include structural features and land use practices that are applied at all scales from the immediate vicinity of wells and springs used for water supply, to the entire groundwater recharge area. In regions where implementation is difficult (e.g. due to lack of financial resources), it is recommended that control measures in drinking-water catchment areas are implemented as a matter of priority before general catchment-wide measures are implemented.

A number of control measures are given below, in order of increasing distance from water supply wells. :

- *Wellhead construction*: microbial contamination of water in wells can be minimized by ensuring that dug wells are surrounded by an impermeable apron (concrete or other material) constructed above ground level to prevent the ingress of surface runoff. Contamination of tubewells can be minimized by ensuring that casing is constructed above groundwater level and has no cracks that will allow water to enter. The annular space surrounding the casing should be sealed with cement to prevent water ingress (for details see Chapter 18).
- *Wellhead inspections and maintenance:* regular, systematic inspection of the structural condition of wells and of activities in the immediate vicinity of water supply wells will help reduce the risk of pathogen contamination caused by construction problems (for details see Chapter 18).
- *Drainage management:* drains and bunds can help ensure that contaminated surface runoff is diverted away from water supply wells and springs (for details see Chapter 18).
- *Backflow prevention:* the use of check valves or other devices on pipe connections to wells can help prevent potentially contaminated water siphoning back into a well.
- *Stock access and waste storage:* stock should be excluded from areas where wells have been constructed by the use of fences. Manure or other waste materials should not be stored or applied within the stock exclusion zone.
- *Water table access:* karstic features (such as dolines and caves) or abandoned mine shafts where there is a direct connection between the land surface and the water table can be fenced-off and drainage diverted to prevent contaminated runoff flowing directly to the water table without being filtered in the soil profile.
- *Storage of manure and other waste materials:* storage areas should have sufficient capacity to accommodate livestock manure during the rainy season or winter months when land application is not possible. The risk of groundwater contamination can be minimized by ensuring these materials are stored on a bounded impermeable surface (preferably covered with a roof). Liquid manure can be stored in covered storage tanks or in appropriately sized and lined wastewater treatment ponds. Covered storage facilities reduce nutrient losses (e.g. ammonia) (EA, 2001).
- *Animal waste treatment:* there are several treatment techniques that can be employed by farmers to ensure that pathogen levels are reduced before animal manures and sewage sludges are applied to agricultural land. They include composting, air drying, lagoon storage, aerobic digestion and lime stabilization.

Composting is one of the most effective techniques (using within-vessel, static aerated pile or windrow composting methods). If the composting process is well managed, pathogen levels can be reduced by more than 4 logs (Sobsey *et al.,* 2003; Gannon *et al.,* 2004). To ensure that pathogens are killed, temperatures within the compost pile should be between 45 ºC and 55 ºC (with short periods exceeding 45 ºC) (EA, 2001). If the compost pile is not covered during the composting process, up to 50 per cent of the carbon and 20-30 per cent of the nitrogen may be lost from the material, reducing the effectiveness of the composted waste as a fertilizer (Goss *et al*., 2001).

- Another effective option for treating animal wastes to remove pathogens is to process them in an anaerobic digester to generate biogas that can be used for household use. Once again, the temperature inside the biogas generator should exceed 55 ºC to ensure pathogens are eliminated from the wastes. Depending on design and operating conditions, pathogen reduction typically is more than 4 logs (Sobsey *et al.,* 2003; Gannon *et al.,* 2004). Aerobic and anaerobic biological treatment processes (including composting and anaerobic digestion) that operate at mesophilic conditions (i.e. below 35-45 ºC) are unlikely to reduce pathogen levels by more than 1-2 logs (Sobsey *et al.,* 2003).
- Lime treatment is another option for treating animal wastes. Pathogen levels in animal wastes can be reduced by a factor of 1000 to 10 000 if sufficient lime is added to raise the pH of the material to 12 for at least a 2-hour period (Sobsey *et al.,* 2003). Long-term storage of manure for several months can also reduce pathogen levels in wastes. Desiccation or air drying to very low moisture levels (<1 per cent) will typically result in more than 4 log reductions. At moisture levels of 5 per cent however, pathogen reduction will typically be less than a factor of 10 only (Sobsey *et al.,* 2003; Gannon *et al.,* 2004). Protozoa such as *Cryptosporidium* and *Giardia* may persist in cyst form.
- *Manure application* – ensuring that manure is not applied immediately upslope of water supply wells or when there is a high risk of rainfall will reduce the risk of groundwater contamination by microbes and nitrate. Incorporation of manure into soil rather than simply applying the material on the soil surface will also greatly reduce the risk of microbes being transported in surface runoff and being washed into poorly constructed wells or through bedrock fractures or karstic features in areas where the soil cover is thin or absent.
- *Pasture maintenance* – ensuring that pasture is maintained in good condition by controlling stock density and through appropriate rotation periods will reduce the mobility of microbes in surface runoff and water percolating into the soil during rainfall events. This may include fences to protect particularly vulnerable features from stock and excreta.

Depending on the size and type of agricultural enterprise, management plans may be useful to define these control measures, their operational monitoring, critical limits and corrective actions (e.g. in animal waste treatment, duration, temperature or pH effectively inactivating pathogens), maintenance of facilities, responsibilities and documentation.

21.2 NUTRIENT MANAGEMENT ON AGRICULTURAL LAND

In the context of groundwater protection for health, nitrate is the only relevant nutrient, and the following discussion will therefore focus on control measures for managing nitrate application. However, nutrient management will often also include phosphorus in order to protect surface waters from eutrophication and its consequences for water quality. Effective nutrient management restricts the movement of nitrogen and phosphorus compounds through soil profiles by minimizing the amount of nutrients that can be leached below crop root zones (source control). This is usually achieved by developing a nutrient budget for the crop, applying nutrients at the correct time using appropriate application methods, applying only sufficient nutrients to produce the crop, and considering specific environmental risks that may be posed by a specific site (e.g. the presence of karst features, etc.). The focus of nutrient management is to increase the efficiency by which applied nutrients are used by crops and thereby reducing the risk of leaching. In many cases, the implementation of nutrient management measures results in less fertilizer or manure being used on crops, reducing overall crop production costs and thus often creating a benefit for the farmer.

The main principles that should apply in nutrient management on crops to protect groundwater quality are:

- determine realistic yields for crops under local soil and climatic conditions (preferably accounting for soil variations on a field-by-field basis) – i.e. not trying to force crops with excessive fertilizer application;
- account for nutrients available to crops from all sources before applying additional fertilizer or manure (i.e. ensuring that only sufficient nutrients are available for crop growth);
- synchronize nutrient applications (particularly nitrogen) with crop needs: nitrogen is most needed during active crop growth, and nitrogen applied at other times is easily leached from soils.

Management practices that address these principles are addressed below.

Preparation of nutrient management plans

Nutrient management plans are often required by local authorities to ensure farmers are using nutrients in an efficient way at the farm scale that prevents groundwater pollution. A plan should contain information about the nature and distribution of soils on the farm, their nutrient status, nutrient leachability and soil erodability, and a description of the proposed and past agricultural practices on the farm, and the proposed measures to prevent groundwater pollution and the erosion of soils from the property. If crops are irrigated, then sufficient rainfall, evaporation and irrigation information should be provided to determine the soil-water balance and assess the risk of nutrient leaching.

Nutrients need to be applied with fertilizers and manures in adequate amounts for a particular crop and close to the time when they are needed for crop growth to minimize the potential for leaching of excess soluble nutrients. Determining an appropriate fertilizing regime for nitrogen, as part of the nutrient management plan, requires application of only the amount of nitrogen that is needed by the crop minus any available nitrogen pools in the soil or from crop residues: The optimum nitrogen fertilizing rate for field crops, applied as chemical fertilizer or manure, can be roughly estimated as follows (modified from Feldwisch and Schultheiß, 1998):

Nitrogen uptake by harvested crop in kg N/dt (see Table 21.2 for examples)

• Realistic estimate of expected yields of a particular crop variety under local soil and climate conditions (dt/ha)

\+ Surcharge for non-harvestable residues, i.e. roots, stubble, leaf fall: depending on the crop, this rate ranges between 20-50 kg N/ha

– Mineral nitrogen pool in the soil at the beginning of the growing season: the nutrient status of soil is best determined from soil analyses, or is estimated from previous experience or long-term records

– Nitrogen delivery from preceding or residual crops remaining in fields (e.g. straw, leaves, herbage) (see Table 21.3 for examples)

– Nitrogen delivery from intercrops/catch-crops: depending on the crop, this rate ranges between 0-40 kg N/ha

– Nitrogen delivery from soils, i.e. from mineralization processes of organic nitrogen during the vegetation period (see Table 21.4 for examples).

In general, less fertilizer should be applied to lighter, sandy soils than clay-rich soils. As a general guide, nitrogen applications in excess of 140 kg/ha on sandy soils and 200 kg/ha on loamy soils in any 12 months commonly lead to nitrate concentrations in groundwater exceeding drinking-water guidelines. An effective approach to avoid excess nitrate leaching into groundwater is to apply manures only at rates necessary to meet crop phosphorus needs, with any additional nitrogen requirements being met with the application of chemical fertilizers or the use of legumes in crop rotations. The amount of fertilizer required to provide 100 kg of nitrogen to soils for a variety of types of fertilizers commonly used in agriculture is summarized in Table 21.5. The use of Global Positioning Systems on agricultural equipment can help optimize application rates to suit variations in soil type across a field.

In addition to determining the appropriate rate, the following measures should be taken when developing a fertilizing regime for a particular crop:

- selecting the appropriate type of fertilizer for a particular crop type and suited for the expected growth rate;
- selecting the appropriate method of applying fertilizer for a specific crop type which ensures maximum nutrient uptake (for example, row fertilizing, top fertilizing, foliar fertilizing);
- ensuring that only crops adapted for local conditions are grown;
- ensuring that the nutrient content of manure and crop residues are properly evaluated to allow a comprehensive nutrient budget to be determined.

In groundwater recharge areas, it is often necessary to reduce fertilizer application rates to protect groundwater quality, and the total nutrient demand of the crop should be considered.

Table 21.2. Nutrient uptake for a variety of crops (modified from Feldwisch and Schultheiß, 1998)

Crop	**Harvested crop** ***corn (I)/straw (II)*** ***beet (I)/leaves (II)*** ***tuber(I)/herbage (II)***	**N-uptake[3] (kg/dt)**			**P-uptake[3] (kg/dt)**			**K-uptake[3] (kg/dt)**		
		I	II[1]	total	I	II[1]	total	I	II[1]	total
Feeding wheat	1.0:1.0	1.8	0.50	2.3	0.35	0.13	0.48	0.50	1.2	1.7
Wheat	1.0:1.0	2.1	0.50	2.6	0.35	0.13	0.48	0.50	1.2	1.7
Wheat for blending	1.0:1.0	2.4	0.50	2.9	0.35	0.13	0.48	0.50	1.2	1.7
Rye	1.0:1.0	1.5	0.50	2.0	0.35	0.13	0.48	0.50	1.7	2.2
Triticale	1.0:1.0	1.8	0.50	2.3	0.35	0.13	0.48	0.50	1.4	1.9
Feeding barley	1.0:1.0	1.7	0.50	2.2	0.35	0.13	0.48	0.50	1.4	1.9
Brewer's barley	1.0:1.0	1.4	0.50	1.9	0.35	0.13	0.48	0.50	1.4	1.9
Oats	1.0:1.0	1.5	0.50	2.0	0.35	0.13	0.48	0.50	2.5	3.0
Spelt	1.0:1.0	1.6	0.50	2.1	0.35	0.13	0.48	0.66	1.4	2.1
Maize	1.0:1.0	1.5	1.0	2.5	0.35	0.13	0.48	0.42	1.7	2.0
Winter rape	1.0:2.0	3.3	1.4	4.7	0.79	0.35	1.1	0.83	4.2	5.0
Sunflower	1.0:3.5	2.8	1.5	4.3	0.70	0.40	1.1	2.0	6.3	8.3
Linseed and flax	1.0:1.8	3.5	0.80	4.3	0.53	0.13	0.66	0.8	1.3	2.1
Field pea[2]	1.0:1.4	3.6	1.5	5.1	0.48	0.13	0.61	1.2	2.2	3.4
Field bean[2]	1.0:1.4	4.1	1.5	5.6	0.53	0.13	0.66	1.2	2.2	3.4
Soya bean[2]	1.0:1.4	5.8	3.7	9.5	0.70	0.57	1.3	1.4	3.3	4.7
Potato (early)	1.0:0.3	0.45	0.10	0.55	0.07	0.01	0.08	0.50	0.17	0.67
Potato (other)	1.0:0.3	0.35	0.10	0.45	0.06	0.01	0.07	0.50	0.17	0.67
Sugar beet	1.0:0.8	0.18	0.28	0.46	0.04	0.04	0.08	0.21	0.42	0.63
Fodder beet	1.0:0.3	0.14	0.11	0.25	0.03	0.01	0.04	0.37	0.12	0.49
Silage maize	-	-	-	1.4	-	-	0.59	-	-	1.7

[1] Related to unit harvested crops. [2] No nitrogen fertilization necessary for legume crops. [3] The amount of nitrogen, phosporus and potassium removed from the soil by growing crops.

Table 21.3. Nitrogen delivery by crop residues (based on Feldwisch and Schultheiß, 1998)

Preceding crop/ residual crop	**N-delivery (kg N/ha)**
Cereals, flax, sunflower, maize for silage	0
Potato, grain maize, annual grass or perennial ryegrass, fallow land (in rotation) without legumes	0-10
Rye, wild mustard species, mustard	10-20
Beet leaves, annual grass or perennial ryegrass (>1 year)	20-30
Grain-legumes (leguminous crops), clover, ley-farming, Lucerne (alfalfa), fallow land (in rotation) with leguminous crops	30-40
Field vegetables, land planting (>1 year), temporary grassland	40-50

Table 21.4. Estimates for mineralization rates for organic nitrogen for a variety of soil types (based on Feldwisch *et al.*, 1998)

Location	**Mineralization rate (kg N/ha/a)**
Humic soils associated with a shallow water table	>100 (in first 4 years) 20-50 (>4-20 years)
Sandy cover soils on moorland	20-50
Colluvium	20-50
Ploughing up of grassland	>100 (in first 4 years) 20-50 (>4-20 years)

Table 21.5. Nitrogen content of commonly used fertilizers (DEP and WRc, 2000; US EPA, 2000)

Fertilizer type	**Fertilizer required to provide 100 kg of nitrogen (kg)**
Inorganic	
Ammonium nitrate	294
Ammonium nitrate and urea	312
Ammonium sulphate	476
Urea	217
Aqua ammonia	500
Anhydrous ammonia	122
Ammoniated superphosphate	2000
Monoammonium phosphate	769
Diammonium phosphate	556
Urea and ammonium phosphate	357
Organic	
Cattle manure	2000-5000
Horse manure	1250-5000
Poultry manure	667-2000

Use of soil surveys

Soil surveys are often carried out to identify variations in soils across the farm, determine likely variations in crop productivity, and identify environmentally sensitive sites. This allows management plans to be developed that take into account local variations. Aerial photographs and existing soil maps are often used to undertake the survey. If the farm is located in a catchment where agriculture is known to have caused nutrient contamination, a nutrient management plan is usually required to help prevent further deterioration of water quality. This will again allow for more responsive management plans to be developed that reflect local variations and conditions.

Appropriate timing of fertilizer application

Fertilizers or manures should be applied during growing seasons when plant uptake is at a maximum. They should not be applied at times when heavy rainfall or melting snow can leach nutrients below plant root zones, making the nutrients unavailable for crops.

Fertilizer or manure applications can be matched to crop uptake rates by splitting the nutrient budget over several applications, use of slow release fertilizers, fertigation (i.e. including small amounts of nutrients in irrigation water) or by applying denitrifying inhibiters to reduce nitrogen loss in soils. Manures should be applied uniformly in accordance with crop needs, and surface applications to no-till cropland should be avoided.

Maintenance of buffers or protection zones around sensitive areas
Protection of drinking-water supplies and sensitive environmental features in agricultural regions may require appropriate buffers to be established to allow nutrient and other contaminant levels to be attenuated. Land in such buffer or protection zones should not be a source of nutrient pollution. Possible land uses include reserves of native vegetation, tree lots or parks used for passive recreation (see also Chapter 17).Their protection and maintenance may be designated in a management plan in order to avoid degradation and loss of function.

Use of crop sequences to minimize nitrogen leaching
Nitrogen leaching to groundwater can be minimized by maintaining a permanent crop cover on fields comparable with permanent grassland. This requires detailed planning of crop sequences. Crops that are especially effective in removing and therefore preserving excessive nitrogen from soils (catch-crops) can be incorporated into the crop sequence. Effective catch-crops include rape, mustard, sunflowers and different grasses that can all bind between 75 and 160 kg N/ha. Optimum nitrogen removal rates can be achieved if catch-crops are sown soon after main crops are harvested and by maintaining a dense vegetation cover (Feldwisch and Schultheiß, 1998).

21.3 MANAGEMENT OF WASTEWATER AND HUMAN EXCRETA USED ON LAND AND IN AQUACULTURE

Although human excreta has been used to enhance soil fertility for several thousand years wastewater has only been widely used as a source of water and nutrients in agriculture over the last few decades. Wastewater from reticulated sewerage or domestic systems is being increasingly used in many countries due to the increasing scarcity of water resources and the high cost of chemical fertilizers. When well managed, the use of wastewater in agriculture will have a minimal impact on groundwater quality. Important control measures for the use of wastewater are set out below.

Nutrient management
Wastewater is a significant source of nutrients, and the set-back distances to sensitive features, rate and timing of application of effluent should be in accordance with management measures for fertilizers and manures set out in Section 21.1. Although wastewater may not contain a sufficient amount of all the nutrients essential for crop growth, care must be taken to ensure that the use of fertilizer supplements does not exceed crop requirements and lead to leaching of chemical contaminants into groundwater. Depending on its source, the composition of wastewater may vary

considerably, and frequent monitoring is required to ensure that its nitrogen content in particular continues to be matched to crop uptake rates.

Application of wastewater and excreta

Wherever possible, wastewater should not be applied to crops by flood irrigation as this irrigation method increases the risk of chemical contaminants and pathogens being leached through the soil profile into groundwater. Preferred irrigation methods to protect groundwater quality are:

- controlled irrigation through furrows
- irrigation by sprinklers
- localized irrigation through drippers

Untreated wastewater and raw excrement should not be applied to crops because of the risk to health of agricultural workers from potential contact with pathogens on crops, and guidelines for the quality of wastewater should always be followed (WHO, 1989; Havelaar *et al*., 2001). Pathogen levels in wastewater can be greatly reduced by holding effluent in stabilization ponds that allow a retention time of 12-18 days, or by chlorination after secondary treatment and filtration (Horan, 1991). Pathogen levels in excreta can also be reduced by storage, or through composting with other organic material (Franceys *et al*., 1992). Details on the requirements for sewage sludge quality are discussed further in Chapter 22. Care should be taken when using treated wastewater to consider aquifer vulnerability, e.g. where soils are thin or locally absent, where there are open wells, sinkholes or other voids that provide a direct conduit to the water table, or where there is a shallow water table because of the risk of contaminating groundwater by pathogens. Determining an acceptable depth to groundwater should take into account hydraulic load and soil conditions as well as depth of the water table (see Chapter 14).

Controlling the source of wastewater

Sewage effluent from catchments with a large component of industrial waste may contain high concentrations of arsenic, heavy metals, pesticides, solvents or hydrocarbons that have the potential to cause groundwater contamination if the wastewater is used for irrigation. Wherever possible, industrial wastewater should not be used on land with crops for human consumption, where soils are thin or locally absent, where there are open wells, sinkholes or other voids that provide a direct conduit to the water table, or where the water table is shallow because of the increased risk of contaminating groundwater. Most regulations for sludge disposal include requirements to assess local conditions before site approval and application of sludge to land (US EPA, 1995; Pedley and Howard, 1997). Controlling the source and quality of sewage effluent, and restricting its use on certain crop types or in certain areas can be more readily accomplished when:

- there are appropriate waste disposal laws and the society is law abiding;
- a public body controls the management of wastes;
- an irrigation project has strong central management;
- there is adequate demand for the crops allowed under crop restriction and where they fetch a reasonable price;

- there is little market pressure in favour of crops not permitted for irrigation by wastewater of a particular quality.

Setback distances for fish ponds
Only treated wastewater should be used in aquaculture and guidelines have been established for these requirements based on overall exposure (WHO, 1989; Havelaar *et al.*, 2001).

Where nonetheless such practices are reality, set back distances can be defined to protect groundwater wells constructed near fish ponds filled with untreated wastewater and fertilized with raw excrement. Consequently, fish ponds should be treated as sources of microbiological contamination that are comparable with sanitation systems. Groundwater supplies can be protected from pathogens from these sources by ensuring that the distances between fish ponds and water supply wells (setback distances) are set using the principles discussed in Chapters 17 and Chapter 22. The latter also provides details of appropriate treatment of wastewater and sludge prior to reuse in aquaculture.

In general, setback distances for fish ponds will be greater than for sanitation systems as the hydraulic loads from leaking ponds is likely to be substantial. This may lead to a localized up-coning of groundwater mound and substantially increasing the local hydraulic gradient and groundwater flow rates. Groundwater is also likely to flow laterally from fish ponds, so wells thought to be upgradient of the ponds may also be susceptible to microbial contamination where there is a significant cone of depression caused by pumping regimes. The risk of pathogen contamination of groundwater can be reduced by slowing the leakage rate of water from ponds through the use of low permeability liners in the ponds (compacted clay or synthetic materials). In densely populated areas establishing adequate setback distances may not be achievable and fish ponds continue to receive wastewater. In such settings, potential health risks should either be managed by treating water pumped from wells near fish ponds, or providing the local population with alternative water sources.

21.4 NUTRIENT AND PATHOGEN MANAGEMENT ON GRAZING LAND

The effects of livestock grazing on groundwater quality can be very variable, and are dependent on site specific conditions such as climate, vegetation density, grazing density and the duration of grazing. The risk of nutrient enrichment of groundwater quality is generally low in semi-arid or arid areas where livestock and animal wastes are uniformly distributed at low densities in the landscape. The risks of groundwater contamination may also be low in humid areas if grazing land is managed correctly. For any grazing measure to work, it must be tailored to fit the needs of the local vegetation and terrain, type of livestock and the culture of the local farming community. However, the following control measures are generally effective in reducing nutrient and pathogen contamination from grazing.

Maintaining vegetation cover on rangeland

Maintaining good quality pasture on rangeland is essential to help hold nutrients in soils, to prevent the erosion of soil and to prevent livestock congregating in small areas of good pasture thereby increasing the risk of localized groundwater contamination problems. This requires maintaining appropriate stocking densities to preserve a uniform cover of native pasture and trees (particularly in semi-arid or arid areas) or planting perennial pasture species adapted for local conditions. In areas with seasonal high temperatures, the preservation of native trees or the establishment of shade trees is important to provide sufficient shade cover to stop livestock congregating in small areas. Maintaining a well distributed water supply for livestock also helps prevent overgrazing in small areas as well as the formation of concentrated urine patches, which on grazed pasture are often the most significant source of nitrate contamination of groundwater.

Use of fencing to exclude livestock from sensitive areas

Livestock should be excluded from riparian vegetation around watercourses, particularly in semi-arid areas where periodic flows in watercourses are often the main source of groundwater recharge. Riparian vegetation plays an important role in minimizing the movement of animal wastes and eroded soil in overland flow into watercourses. Other sensitive areas like sinkholes in karstic areas should be fenced to prevent animal access.

Limit stocking rates in groundwater recharge areas

In drinking-water catchments where the protection of groundwater quality is a high priority, animal stocking rates should be restricted to minimize the risk of groundwater contamination by nutrients and pathogens. A stocking rate of less than two horses or cows per ha has been found to be an effective protection measure in particularly sensitive areas with very sandy soils (WRc, 1998). In Germany, recommended stocking rates are 1.3 to 1.4 large animal units per ha (where an animal unit is equivalent to an animal of about 500 kg). Optimizing livestock diets also help to minimize the quantity and nitrogen content of manures.

Use of grazing management plans

The development of farm-specific grazing management plans is an effective control measure for protecting groundwater quality from this land use while maintaining or increasing the economic viability of the grazing operation. The steps to developing an effective grazing management plan are to (US EPA, 2000):

- undertake an inventory of existing resources and pasture condition;
- determine management goals and objectives;
- map out grazing management units;
- develop and implement a grazing schedule;
- develop and implement a monitoring and evaluation strategy.

21.5 MANAGEMENT OF ANIMAL FEEDING OPERATIONS AND DAIRIES

The often severe water quality problems associated with animal feeding operations and dairies are due to the high concentrations of animals and their accumulated wastes, and the large amount of wastewater that can be generated from stormwater runoff and the washdown of the facilities. The risk of groundwater pollution occurring can be minimized by the proper siting of the facilities, by waste and water management practices and by reducing the amount of nutrients excreted in wastes through a well managed feeding regime.

Siting animal feeding operations and dairies

One of the major considerations in preventing groundwater pollution from an animal feeding operation or dairy is the location of the facility. For new facilities and expansions to existing facilities, consideration should be given to siting the facility away from surface waters, areas with a high leaching potential, sinkholes or other environmentally sensitive areas, and in areas where sufficient land is available to apply wastes to soils at rates which will not affect groundwater resources.

The US EPA (2000) indicates that there are eight critical factors to be considered when siting and operating a feedlot. These are:

1. *Divert clean water*: siting or management practices should ensure that clean runoff does not touch stock holding pens or manure storage areas.
2. *Prevent seepage*: buildings and storage facilities should be designed and maintained to prevent contaminated water seeping into groundwater.
3. *Provide adequate storage*: liquid manure storage systems should be designed to safely store the quantity of wastewater produced in the feedlot plus additional runoff from intense storms (often designed for a 25 year, 24 hour storm). Dry manure should be stored under cover wherever possible to prevent the generation of additional contaminated runoff.
4. *Apply manure in accordance with a nutrient management plan*: it is important that manure use is seen as part of an overall nutrient management strategy for a farm (see above).
5. *Manage land where manure spreading is taking place*: land being used for manure disposal should be well managed to prevent erosion that can cause nutrients to be moved offsite. Management measures include proper stock control and the use of vegetated buffers and filter strips.
6. *Record keeping*: records should be kept of the amount of manure generated and the disposal method used. This will help assess the effectiveness of a nutrient management plan, and allow it to be revised if necessary.
7. *Mortality management*: dead animals should be managed in a way that minimizes impacts on groundwater. The British Columbia government in Canada recommends that animal disposal in pits is not within 120 m of wells used for water supply or within 30 m of a surface water feature. The guidelines (BC MAF, 2000) recommend that the base of disposal pits is at least 1.2 m above the seasonally highest water table, and that disposal pits have at least 1 m of earth cover.

8. *Consider the full range of environmental constraints*: when expanding an existing facility or siting a new feedlot, consideration should be given to the distance of the facility from surface water features, from areas where groundwater is highly vulnerable to contamination, and from sinkholes or other features that allow surface runoff direct access to the water table.

Solid waste management practices

Manure should be removed from animal pens at frequent intervals. It is recommended that it is stockpiled in a roofed facility on an impervious floor to prevent leaching by rainfall. Manure can be stored for an extended period until it is used on the farm or is moved offsite for use elsewhere. Maintaining low moisture content in the manure will minimize odour problems and the generation of leachate. If sufficient space is available, manure can be aerobically composted in turned piles or rows to improve its performance as a soil amending agent and to reduce pathogen levels.

As discussed in Section 21.2 above, manure must be applied to soils at rates which will minimize groundwater contamination by nitrate, and the appropriate application rate should be determined by carrying out tests on local soils.

Water and liquid waste management practices

Stormwater runoff from roofs and paved areas should be channelled away from feedlots or dairy pens using bunds and drains to ensure it does not become contaminated with animal wastes. It is recommended that stormwater is collected in a lined settling pond and can be disposed of by irrigation under suitable weather conditions.

Runoff from areas contaminated with animal wastes should be channelled to a series of ponds for storage and treatment to reduce the BOD and nutrient content before disposal by irrigation or other means. At least two fully lined ponds are required to adequately treat the wastewater. The first pond allows solid organic material to settle out and be degraded under anaerobic conditions by microorganisms. Water from this pond is decanted in a shallower pond which is aerated by wind action, and which allows the penetration of sunlight to help reduce levels of microorganisms before water is disposed of by irrigation under suitable weather conditions.

The storage and treatment ponds should have sufficient capacity to store water over winter or the wettest period of the year, and should be able to store water from intense rainfall events. Regulations for the design and capacity of storage ponds vary from jurisdiction to jurisdiction. A general guide given by BC MAF (2000) recommends that the volume of storage of ponds can be estimated by the following formulas:

Runoff from paved feedlots:

$$V = A \text{ x } (0.48\ P_m + 0.65\ P_s) \qquad \text{(Eqn. 21.1)}$$

Runoff from unpaved feedlots:

$$V = A \text{ x } (0.22\ P_m + 0.45\ P_s) \qquad \text{(Eqn. 21.2)}$$

Runoff from manure storage areas:

$$V = A \text{ x } (0.25\ P_m + 0.65\ P_s) \qquad \text{(Eqn. 21.3)}$$

where V is the volume of storage, A the area contributing to runoff, P_m the sum of six-monthly winter precipitation (rainfall plus an equivalent water depth of snowfall), and P_s the 24-hour precipitation from a storm expected once in 25 years.

Wastewater treated as outlined above will in most cases not be of a suitable quality to discharge to waterways, but may be disposed of by irrigation under suitable conditions. As discussed above, wastewater should not be applied to land unless the soil nutrient status has been determined, and its use is consistent with the nutrient management plan developed for the farm. Sufficient land area should be available for a 10 to 14 day rest period between applications on a given part of the farm, the objective being to alternate between anaerobic and aerobic conditions in the upper part of the soil (shorter periods may be possible under dry summer conditions). Crops or pasture should be maintained to take up as much nitrogen and phosphorus as possible to minimize the risk of groundwater pollution occurring.

21.6 PESTICIDE MANAGEMENT

As some pesticides in current use are toxic at low concentrations and can cause groundwater contamination if used incorrectly, these chemicals need to be stored, used and disposed of with great care to minimize groundwater contamination problems. In general, pesticides should be applied to soils at the lowest possible rate which controls the pest problem to reduce the potential for leaching. Control measures that reduce the risk of groundwater contamination by pesticides include the following:

Undertake an inventory of current and historical pest problems
Adequate pest control requires a good understanding of what insect pests and weeds are a problem in each field so that pesticide spraying can be well targeted at appropriate application rates. Agricultural extension officers, universities or specific consultants can help identify the distribution of weeds and insect pests on individual farms. The costs entailed in compiling pest inventories are usually rapidly recovered by reductions in the amount of pesticides applied to crops.

Assess the potential for the leaching and runoff of pesticides from farms
Pesticides should not be applied near features that allow direct access to the water table such as karst features, abandoned wells or drainage wells. Adequate buffers should be maintained from water supply wells, surface water bodies and other sensitive environmental features. Pesticide application rates may need to be reduced in areas with light, sandy soils and a shallow water table to reduce the risk of groundwater contamination. Application rates may also need to be reduced on heavy soils with steep slopes to prevent surface runoff that could infiltrate into soils further downslope. Cropping practices such as no-till methods can greatly reduce the risk of runoff from steep slopes on heavy soils.

Increase organic matter in soils
Increasing the organic content of soils by the application of composts or manures can greatly increase the binding capacity of soils and reduce the risk of pesticide leaching.

Proper construction of pesticide storing and mixing areas

The risk of groundwater contamination taking place is often greatest at sites that are used for storing and mixing pesticides before application to fields. The construction of dedicated storage and mixing areas can greatly reduce the risk of contamination occurring through spills. These should have an impermeable (concrete) floor and be surrounded by curbing to contain any spills, and the area should be large enough to confine at least 125 per cent of the displaced volume of liquids housed in the storage area. Runoff from the mixing area should be stored in tanks or sealed ponds to allow water to be removed for treatment or to be applied to fields.

Pesticides in small containers should be stored inside a shed on wooden palettes or shelves to keep the containers off the floor to minimize corrosion of containers. Large bulk storage tanks containing pesticides should be elevated so that leaks are easily seen. Regular monitoring and maintenance of the integrity of structures to contain pesticides are important and would be included in a management plan.

Special care needs to be taken with the handling and transfer of pesticides to the distribution containers and subsequent washing down of vehicles and equipment. It has been estimated that over 50 per cent of observed contamination can occur from these practices if executed poorly.

Use of cropping measures and biological controls to reduce pesticide use

There are a variety of cropping measures that can be used to reduce the use of pesticides on crops. There are also an increasing number of new crop varieties which only require low applications of pesticides to achieve a high resistance to fungal diseases and to damage by insects and nematodes.

Crop rotations can interrupt pest build-up by eliminating the host plant or by changing the physical conditions that allow the use of smaller amounts of pesticides. An example of this is corn-soybean rotation in which broadleaf weeds are more easily controlled in the corn crop and grass weeds are more easily controlled in soybean crop. Some plant species have allelopathic properties when used in rotations; that is, they can reduce pest populations in subsequent crops. For example, a rye cover crop may reduce weed populations in subsequent crops.

The use of trap crops can also greatly reduce the use of pesticides. These are plant species which are more attractive to particular pest species that the main crop, so pesticide applications can specifically target these plants. Trap crops can either be planted adjacent to main commercial crops, or planted at an earlier time to ensure pest control before the main crop is harvested.

Increasing the biological diversity on farms by retaining remnant vegetation or maintaining hedgerows can also indirectly reduce the need for pesticides by increasing the number of predator species. In general, agricultural monocultures create simple environments where pests have little or no competition from other species or predators. Having a broad array of plant species on farms diversifies the habitat and helps reduce pest populations. Insect predator species may be introduced into fields and the use of specific pesticides to target only pest species can enhance the effectiveness of predators.

Use of low-toxicity or biological pesticides

Highly toxic or environmentally persistent pesticides can often be replaced with less toxic or persistent equivalents. The use of less harmful pesticides can be increased by management measures such as the use of financial incentives, specific training Biological pesticides include microorganisms which are pathogens to specific insect pests, and the use of pheromones to lure or trap insects. They are very specific to a target species, are effective at low concentrations and generally pose little or no threat to human health or other species. Pheromones can also be used to disrupt the reproduction of insect pests or attract predators and parasites.

21.7 IRRIGATION WATER MANAGEMENT AND DRAINAGE

Most of the groundwater quality problems associated with irrigated agriculture are due to the inefficient use of water which increases leaching of water and soluble salts through the soil profile. Poorly managed crop irrigation and drainage schemes, including poor maintenance of irrigation structures, can be a major cause of health and environmental problems.

Irrigation scheduling practices

Proper scheduling of the application of water is a key element in the management of irrigated agriculture. Scheduling should be based on knowing the daily water use of the crop, the water-holding capacity of the soil, the lower limit of soil moisture for each crop and soil, and measuring the amount of water applied to crops. Natural precipitation should also be considered and adjustments made in irrigation schedules. Practices that help manage irrigation scheduling are:

- metering of water flow rates;
- using soil and crop water use data to determine the timing of water applications;
- reducing hydraulic load by using efficient irrigation systems.

Practices for the efficient application of irrigation water

Irrigation water should be applied in a manner that ensures an even distribution of water and efficient use by crops and minimizes runoff or deep percolation. The method of irrigation varies considerably with the type of crop grown, topography, soils and local cultural factors. However, there are several practices that are particularly effective for applying and controlling the distribution of irrigation water. These include:

- *drip or trickle irrigation systems*: water is applied at low pressure to crops with minimal evaporative losses;
- *sprinkler systems*: there are a large variety of sprinkler systems for applying water under pressure to crops;
- *water control structures*: the use of furrows, contour levees or contour ditches can help control the spread of water applied in an irrigation area;
- *irrigation field ditches*: permanent structures used to convey water from the source of supply to a field or fields in a farm distribution system;

- *land levelling*: reshaping the surface of the land to planned grades to ensure that water does not pool in certain areas causing excessive infiltration or salinization, or else runoff at high velocities causing erosion.

Efficient use of runoff water

Runoff from precipitation or excess irrigation can be captured, stored and used as part of an irrigation system to improve the overall efficiency of the system and minimize the potential for leachate infiltration.

Drainage water management

Drainage water from an irrigation system should be managed to reduce the potential for leachate to contaminate groundwater and reduce erosion. A well planned and maintained drainage system should be an integral part of the design of an irrigation system. Practices that can be incorporated into a drainage system include the use of:

- *filter strips*: an area of vegetation for removing particulate matter from runoff and wastewater;
- *surface drainage field ditches*: a graded ditch for collecting excess water in a field;
- *sub-surface drains*: a conduit such as a perforated pipe installed beneath the ground surface to collect and convey excess irrigation water.

Drainage is also commonly used in areas with a naturally shallow water table to make land suitable for agriculture. Where soils naturally contain high concentrations of sulphide minerals, wide, shallow drains should be constructed rather than conventional deep drains. This minimizes the disturbance of sulphides and reduces the risk of forming acid sulphate conditions.

21.8 MONITORING AND VERIFICATION OF MEASURES CONTROLLING AGRICULTURAL ACTIVITIES

Table 21.6 summarizes selected examples of the measures proposed above to control groundwater contamination from agricultural activities. These include planning, physical structures to prevent leachate and operational controls to ascertain implementation of management plans. In some settings, some of these control measures may be suitable for integration into the WSP (see Chapter 16) of a drinking-water supply and become subject to operational monitoring in the context of such a plan.

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 effective. Table 21.6 therefore includes options for surveillance and monitoring of the control measure examples given. Most of these monitoring options focus on checking whether controls are operating as intended, rather than on contaminant concentrations in groundwater:

- For control measures in the context of planning, surveillance will review how well land use is taking aquifer vulnerability into account, e.g. with respect to siting of animal feedlots and treatment of their runoff, or whether management plans for nutrient and pesticide application exist and are adequate. Monitoring will include site inspection to assess whether plans are being implemented.

- For control measures addressing design and construction, monitoring is largely through site inspection to ascertain their adequacy and integrity, e.g. whether a feed-lot is properly drained, whether the storage tank for liquid manure is covered, whether irrigation systems are constructed as indicated in the management plan or permit, and whether maintenance of structures is adequate.
- For control measures addressing day-to-day routine operations, monitoring focuses on assessing whether the specific restrictions, limitations or management plans imposed to protect the drinking-water aquifer are being followed, e.g. by inspecting farm records on agrochemical use, counting heads of stock, or sampling the nutrient content of soils.

NOTE ▶ *The implementation of control measures such as those suggested in Table 21.6 is effectively supported if the stakeholders involved collaboratively develop management plans that define the control measures and how their performance is monitored, which corrective action should be taken both during normal operations and during incident conditions, responsibilities, lines of communication as well as documentation procedures.*

The implementation of control measures protecting drinking-water aquifers from agriculture is substantially facilitated by an environmental policy framework (see Chapter 20).

In addition to the operational monitoring of the functioning of control measures, overall groundwater monitoring is important to verify comprehensively that agrochemicals and manure are not contaminating aquifers used for drinking-water abstraction, i.e. that the management concept for the catchment is adequate and safe. With respect to fertilizers and manure this would typically include nitrate and potentially, for the latter, also indicators for pathogen occurrence or even pathogens of particular concern in the respective setting. With respect to pesticides, chemical analyses for monitoring may be facilitated by information on the range of substances typically applied in the region.

NOTE ▶ *Options for monitoring suggested in Table 21.6 focus on control measures rather than on groundwater quality. Analysis of selected parameters in groundwater which indicate leaks of containments for agrochemicals or manure 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 the overall drinking-water catchment management.

Table 21.6. Examples of control measures for agriculture and options for their monitoring and verification

Process step	Examples of control measures for agriculture	Options for their monitoring and verification
PLANNING	Define criteria for exclusion or restriction of agricultural activities (e.g. stock density, type of crop) in vulnerable drinking-water catchments (e.g. implement protection zones)	Monitor land use within vulnerable areas/protection zones and ensure that restrictions are implemented (site inspection)
	Require permits for the location, design and operation of feedlots in vulnerable drinking-water catchments	Review plans and applications for permits for agricultural activities in relation to vulnerability of drinking-water aquifer
	Require nutrient and pesticide management plans with specific limitations on amounts and timing of agrochemical, manure and sludge application	Audit nutrient and pesticide management plans
	Restrict wastewater irrigation near boreholes, in vulnerable groundwater recharge areas or in drinking-water protection zones (permit process)	Monitor selected parameters in groundwater which indicate contamination with agrochemicals and/or pathogens
DESIGN, CONSTRUCTION AND MAINTENANCE	Construct and maintain safe containments for agrochemicals and adequately sized, impermeable and bonded sites for pesticide mixing and cleaning of equipment Install and maintain safe storage tanks for liquid manure	Inspect structures and review management plans Monitor selected groundwater parameters (agrochemicals, indicator organisms) which would indicate leakage
	Prevent chemical use and animal access near features that allow direct access to groundwater (e.g. sinkholes, abandoned mineshafts, wetlands with groundwater throughflow)	Ensure features are fenced off with appropriate set-back distances through statutory controls and inspections
	Apply drip irrigation to avoid water table drawdown and overdraught	Inspect irrigation system Monitor groundwater table
OPERATION	Control implementation of restrictions on agricultural activity in vulnerable drinking-water catchments	Inspect farm records of agrochemical application Count heads of stock
	Control implementation of pathogen, nutrient and pesticide management plans (i.e. choice, amounts and timing of application)	Inspect timing and amounts of manure application; review management plan and documentation Analyse residual nitrogen or phosphorus in the soil at beginning of growing season to determine fertilization needs
	Grow winter cover crops to consume excess soil nitrogen	Conduct visual site inspection
	Match irrigation to crop needs	Inspect and monitor drainage Inspect farm records on water use Audit irrigation plans

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22

Human excreta and sanitation: Control and protection

G. Howard, B. Reed, D. McChesney and R. Taylor

The safe disposal of human excreta is essential for public health protection. The unsafe disposal of excreta is a principal cause of the transmission of pathogens within the environment and improvements in excreta management provide significant reductions in diarrhoeal disease (Esrey *et al.*, 1991; Esrey, 1996; Hutton and Haller, 2004). Access to improved sanitation lags behind access to water supply throughout much of the world and in particular within developing countries. It is estimated that over twice the number of people lack access to improved sanitation than lack access to an improved water supply (WHO and UNICEF, 2004).

Excreta disposal technologies may represent a risk to groundwater and inappropriate design, siting and maintenance of sanitation facilities can contaminate groundwater and thus lead to public health risks from drinking-water. Chapter 10 provides an overview of these risks and how these may be assessed. However, the health risks from the absence of improved excreta disposal are likely to exceed those posed by contamination of groundwater from sanitation alone, and this must be borne in mind when planning improvements in sanitation and groundwater protection. Furthermore, the lack of excreta disposal may be a direct cause of contamination of groundwater sources and improvements in sanitation

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may also deliver improvements in microbial quality in groundwater (Howard *et al.*, 2003).

This chapter provides an overview of some of the options for managing groundwater pollution risks derived from sanitation, both for on-site and off-site methods. These include planning, design and construction of facilities, as well as monitoring and managing their safe operation. Important aspects discussed in the context of planning are siting decisions and infrastructure changes that will help reduce risks, and balancing the sometimes competing needs for better sanitation and groundwater protection. The end of the chapter summarizes some major control measures that can be used to provide protection of groundwater through effective management of sanitation.

NOTE ▶ *In developing a Water Safety Plan (Chapter 16), system assessment would review the efficacy of control measures and management plans for protecting groundwater in the drinking-water catchment from human excreta and sanitation. Chapter 10 provides the background information about the potential impact of wastes on groundwater and provides guidance on the information needed to analyse these hazards.*

This chapter introduces options for controlling risks from human excreta and sanitation. In some settings, water utilities or communities hold the responsibility both for drinking-water supply and for sanitation and in these, measures to control risks from human excreta may readily become part of a Water Safety Plan. Where the responsibility for sanitation falls outside that of drinking-water supplier, close collaboration of the stakeholders involved is important to implement, upgrade and monitor these control measures. This may be initiated by water suppliers and supported by the health authority which is usually responsible for the surveillance of both the drinking-water supply and sanitation facilities.

22.1 BALANCING INVESTMENT DECISIONS

Both drinking-water source and sanitation improvements are important to protect public health but, as noted in Chapter 10, excreta disposal systems may lead to groundwater contamination and therefore potentially lead to a risk to public health derived from use of this water for drinking. This has led to a debate among water and sanitation professionals regarding the need to balance risks derived from the contamination of drinking-water from sanitation systems with the health risks posed by an absence of effective excreta disposal.

All decisions about technology and interventions will have cost implications for the users and decisions may be required to balance competing risks. Very good technical solutions that users cannot afford will not deliver significant improvements in health. The evidence suggests that the nature of the competing risks and priorities for investment are different between different communities and may change over time.

The issues are often different in rural and urban areas. In urban areas, although contamination of groundwater may be greater, alternative water sources are often available within easy reach or more distant sources can be developed and water delivered to urban populations in a cost-effective manner. In rural areas, although contamination risks may be lower from reduced discharge or leaching of contaminants, alternative sources may be limited or their development to provide water to rural households may be very expensive. Therefore control of risks from sanitation design, construction and maintenance may be more critical. These issues apply equally in developed and developing countries.

In communities in developing countries where improved sanitation facilities do not exist, setting stringent requirements for sanitation facility design and construction to meet criteria to prevent groundwater pollution may be counter-productive, unless the risk is very significant. Such criteria may make sanitation improvements too expensive for many households resulting in continued lack of sanitation and ongoing disease transmission (Mara, 1996). Where the construction of sanitation will represent a very significant risk of groundwater contamination, decisions will be required as to whether changes in water supply or sanitation are more cost-effective (Franceys *et al.,* 1992).

Although microbial contamination of groundwater from excreta disposal should be minimized, some groundwater pollution may have to be accepted in order to reduce a greater health risk from a lack of excreta disposal (Cairncross and Feacham, 1993; ARGOSS, 2001). Where a groundwater source is linked to a piped water supply, public health risks derived from microbial contamination of groundwater from on-site sanitation may be controlled by treatment of the water prior to distribution. Where water is collected by hand, it may be more cost-effective to provide an alternative (piped) water supply bringing in uncontaminated water than to change sanitation designs (Franceys *et al.*, 1992). If this approach is followed then action may be required to close the previously used groundwater source, as evidence from several developing countries indicates that use of untreated groundwater sources is common even when better quality alternatives are available (Ahmed and Hossain, 1997; Howard *et al.*, 2002).

In more developed countries, water source substitution may not be more cost-effective than changing the sanitation facility and the public health demands for groundwater protection may be greater than those associated with sanitation. As a result, investments in upgrading sewer systems, installing sewers into previously unsewered areas or introducing on-site sanitation systems that have a lower impact may all be preferred solutions. Experience suggests that decisions should be based on each individual case and blanket solutions are rarely applicable.

The contamination of groundwater from chemicals derived from human excreta and sewage may be more difficult to control and the treatment of drinking-water less certain to remove or reduce concentrations to an acceptable level. Thus source protection will become more important. For instance, the removal of nitrate through treatment is unlikely to be feasible in most situations and removal of pesticides and organic chemicals may be difficult and expensive. Where there is extensive nitrate contamination, blending with other low-nitrate waters may be required to reduce nitrate levels in final waters, although this is only feasible for piped water supplies where alternative sources of sufficient quantity exist. For other chemicals, blending or use of granular activated carbon may be needed to reduce concentrations to acceptable levels.

In such cases there may be greater need for source protection, particularly in those countries where disease burdens from microbial hazards from drinking-water are low. Thus in developed countries, it may be cost-effective to increase groundwater protection as the potential threats of chemical contamination of groundwater sources are relatively significant.

In developing countries, the microbial health risks posed by inadequate sanitation often so greatly outweigh the risks to health associated with possible groundwater contamination by chemicals that rising levels of contamination may be acceptable if this allows improved sanitation. However, in making these decisions, it is important to take into account long-term usage of water resources. For instance, because nitrate is conservative in many groundwaters controlling nitrate pollution is important for securing the long-term viability of the aquifer. Controlling nitrate risks for this reason is best justified where groundwater represents the long-term option as a source for domestic supply.

22.2 SELECTING THE RIGHT SANITATION TECHNOLOGY

The first stage in the management of sanitation in order to protect against groundwater contamination is to select the right technology for the local environment. This requires that data is collected on the local hydrogeological conditions (Chapter 8) and the role of groundwater in water supplies within a region or the country. Sanitation technology selection will not be based solely on concerns regarding risks of groundwater contamination. Community preferences, usual methods of anal cleansing, available resources and costs of technology options should all be considered in this process (Franceys *et al.*, 1992; Cotton and Saywell, 1998). In many cases these concerns will take priority over groundwater quality concerns, but it is important that attention is also paid to groundwater pollution risks in the decision-making process.

The links between water supply service and sanitation options cannot be ignored. As water supply service levels increase, so will water consumption, thus increasing the volume of wastewater that must be disposed of. Using sanitation technologies that are not designed to take large volumes of wastewater will not be appropriate and water-based systems or sanitation systems that separate effluent and solid material should be considered. Equally, the use of flush toilets and other water-based systems will not be appropriate where the water supply service is only a public tap, dug well or other form of communal supply. Intermediate levels of service (single on-plot tap) may be suitable for some forms of modified sewerage, but will not allow the use of conventional sewerage.

It should be noted that sewerage systems do not necessarily confer additional benefits to health or groundwater protection over those offered by on-site sanitation. As noted in Chapter 10, sewers often leak and there is significant evidence of their role in causing pollution of groundwater. Decisions on whether on-site or off-site sanitation systems will be used will also depend on cost-benefit analyses of the options, including costs for sewer maintenance, which are beyond the scope of this text. In rural areas of many developed countries, on-site sanitation options remain the most viable solution, e.g. the use of septic tanks is common in the USA (Lerner, 1996). Provided such facilities are properly sited, designed, constructed and maintained they provide a level of service equivalent to a connection to a sewer and represent only a limited risk to groundwater. Some forms of ecological sanitation are also designed for use in developed countries where water consumption is high. Therefore on-site sanitation solutions should not be viewed as limited only to developing countries.

Maintenance of sanitation facilities is an important issue for any technology chosen, and the implementation of routines for inspection and maintenance may be supported by their documentation in management plans of the stakeholders responsible for these facilities.

22.3 MEASURES FOR CONTROLLING RISKS FROM ON-SITE SANITATION

In many developing countries access to water supply and sanitation remains low and there is an urgent need to provide both improved water supply and a safe means of excreta disposal (WHO and UNICEF, 2000). In many rural and peri-urban communities (including poor marginalized communities within urban centres) it is likely that improved access to sanitation facilities will be in the form of on-site sanitation (Mara, 1996; Cotton and Saywell, 1998; ARGOSS, 2001).

In this section some key issues relating to the risks posed to groundwater quality from on-site sanitation and the potential means by which this may be reduced through design (including siting), construction and maintenance are reviewed. It is not intended to provide a detailed description of how to design and construct such facilities, but rather the specific measures that can be used to protect groundwater. For details on design, construction and operation criteria, readers are referred in particular Franceys *et al.* (1992) and in relation to urban areas, Mara (1996).

22.3.1 Siting of on-site sanitation facilities

A key strategy for the control of risks from sanitation systems and human excreta is to ensure that they are sited so that the risk posed to sources of groundwater used for drinking-water supplies is minimized. As a significant source of pathogens, the control of sanitation systems in relation to groundwater sources is a key consideration when defining groundwater protection zones for microbial quality (as discussed in Chapter 18). Sanitation systems should not, by preference, be located within the zone of protection for microbial quality and definitely not in close vicinity to a wellhead or spring (Chapter 17). However, in more densely populated areas it may not be feasible or cost-effective to remove the sources of pollution and therefore engineering improvements to the sanitation facilities may be required.

Site selection of sanitation facilities is an important control measure to protect groundwater from human excreta. In many developing countries, recommendations are often made regarding siting of latrines with respect to groundwater sources. These are often developed separately from (and usually before) groundwater protection zones.

Set-back distance recommendations range from simplistic to more sophisticated approaches based on hydrogeological conditions. Pickford (1995) notes recommendations from India for pit latrines to be located some six m downhill of the nearest water source. Such recommendations should always be treated with some caution. Although the hydraulic gradient of shallow groundwater typically follows the ground surface, it should be borne in mind that where the well is equipped with an electric submersible or other form of pump, there will be a substantial draw-down. Therefore contaminants can be drawn into the well from areas downhill and physical location may not always provide adequate protection.

In many countries, single-distance criteria are used. A distance of 15 m is a commonly used criterion, based on suggestions by Wagner and Lanoix (1958). The weaknesses in using these approaches were highlighted by Lewis *et al.* (1982) who noted that this distance may be overly conservative in some hydrogeological environments (thus limiting health gains from sanitation) and insufficient in other environments with rapid flow rates. Lewis *et al.* (1982) suggested that set-back distances should be established based on local hydrogeological conditions (such as water table depth, nature of unsaturated zone) and the hydraulic load from the latrine.

In South Africa, for example, DWAF (1997) developed a framework for selecting separation distances using contaminant risk assessment based on:

- whether the site for sanitation development overlies a major aquifer;
- the proposed use of groundwater;
- the depth to the water table;
- the type of aquifer;
- presence of existing latrines within 50 m and upgradient;
- evidence of contamination.

Other work in South Africa has recommended an approach that takes into account estimation of pollution risk based on travel time for microbes, mass balance for nitrate and using a probabilistic approach for contamination exceeding specified targets (van Ryneveld and Fourie, 1997).

One problem noted with the definition of set-back distances is that these do not always take into account that different types of technology are likely to have different levels of pollution potential. Pit latrines commonly are significantly deeper than septic tanks and tend to rely on infiltration of leachate through the surrounding soil. Pour-flush latrines have a much higher hydraulic load than dry latrines and as a result have a greater pollution potential. Septic tanks typically receive relatively large volumes of wastewater and therefore if not constructed properly, may lead to a significant hydraulic load and increased pollution potential. This is reduced through ensuring that the tank is watertight and that effluent is discharged into drain-fields and soakaways at a much shallower level.

In addition to set-back distances, hydrogeological data are often used to identify areas where groundwater-fed sources are particularly susceptible to contamination. A widely used method, for example, is known as DRASTIC (Aller *et al*., 1987; US EPA, 1992) which employs several hydrogeological factors in order to develop an index of the vulnerability of groundwater to contamination (for more detail see Chapter 8.1.4). The method is, however, data intensive and does not include factors that relate specifically to the risk to groundwater posed by sewage and sewage-derived microorganisms. DRASTIC also does not provide any site-specific guidance. The index may, however, provide a worthwhile framework for assigning set-back distances based on different levels of risk. A framework similar to DRASTIC, designed specifically to assess the vulnerability of groundwater to contamination by sewage-derived *Cryptosporidium parvum*, has been developed in the United Kingdom by Boak and Packman (2001).

Recent research in developing countries has attempted to develop guidance without requiring detailed hydrogeological information in order to determine set-back distances for pit latrines (ARGOSS, 2001). Risk assessments are defined for three scenarios (localized microbial contamination; widespread microbial contamination; and widespread nitrate contamination). For separation distances related to microbial quality, decisions are based on a time of travel estimation that includes hydraulic and pollutant loading as well as the attenuation potential and survival of microbes. Set-back distances are estimated from a set of standard tables and figures that have been calibrated with data from field studies and analysis of published works. This approach uses a three-tier approach to risk as shown in Table 22.1 below. Figure 22.1 provides an example of the flow-chart for decision-making; Box 22.1 provides a case study of applying this methodology.

More qualitative approaches to defining separation distances using available data can be used based on statistical analysis of water quality and sanitary inspection data (ARGOSS, 2001; Howard *et al*., 2003). These have been shown to be robust in supporting water and sanitation planning and offer an effective way to determine siting requirements based on local conditions when there is limited hydrogeological data available.

Table 22.1. Levels of pathogen risk in relation to travel time (adapted from ARGOSS, 2001)

Level of risk	**Comments**
Significant risk	Travel time under 25 days (breakthrough of both viral and bacterial pathogens in significant numbers possible)
Low risk	Travel time above 25 days (primarily related to the potential for viral breakthrough) but under 50 days
Very low risk	Travel time above 50 days (unlikely to have significant breakthrough of any pathogens, although low risk of viral breakthrough remains)

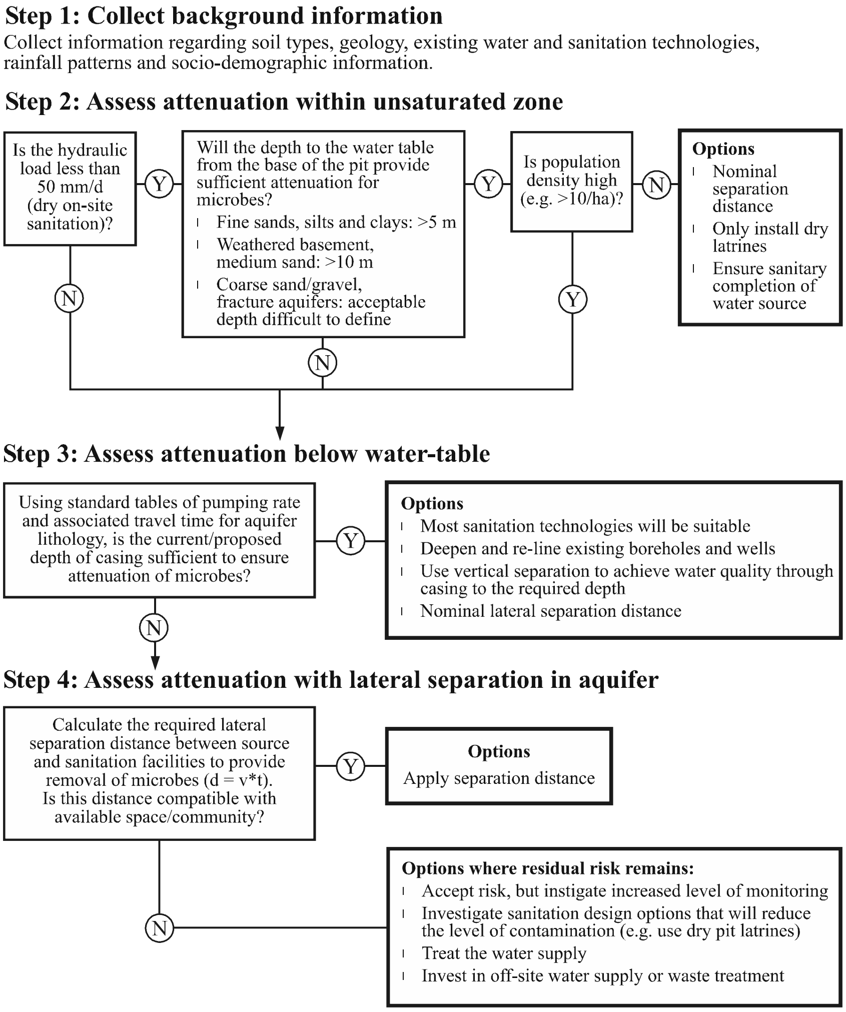

Figure 22.1. Flow chart for assessing the risk of microbiological contamination of groundwater supplies via aquifer pathways where on-site sanitation is being installed (modified from ARGOSS, 2001)

Box 22.1. Calculating the separation distance between latrines and protected springs in Wakiso District, Uganda

A study to determine acceptable separation distances between latrines and water points was undertaken in Nabweru sub-county in the District of Wakiso, Uganda, a rural area with a population density ranging from 9-12 people per ha. The population relies on non-piped sources of water (boreholes, dug wells and springs) and pit latrines for sanitation. The area is hilly with swamps in low-lying areas and most springs are found on the lower slopes.

The soil is a fine sandy silt, with clayey soils found in the swampy areas. The area receives about 1600 mm of rainfall a year in two principal wet seasons (March to June; August/September to November). The depth to water table across the area ranges from 30 m in higher areas (where boreholes and dug wells are found) to 5-8 m close to the protected springs. Pit latrine depths typically range from 6-10 m in depth.

The assessment used the ARGOSS methodology and took into account the different technology types and the geological setting. It was concluded that as dry pit latrines were used, the hydraulic load would be less than 50 mm/day and therefore there was potential for unsaturated zone attenuation. As the depth to water table in higher levels was 20 m below the base of the deepest pits, it was concluded that unsaturated zone attenuation would limit all microbial risks in these areas and a nominal horizontal separation between latrines and water sources would be adequate.

In lower-lying areas, the depth to the water table beneath the base of the pits was only 1-2 m and therefore it was concluded that the desired horizontal separation distance should be calculated.

The horizontal separation distance d was calculated using:

$$d = v*t$$

where v is velocity and t is time. The velocity was calculated by using:

$$v = K_i/\varphi$$

where K is the hydraulic conductivity (permeability), i is the hydraulic gradient, and φ is porosity.

For this area, the permeability and porosity were estimated using the lithology as a guide. A permeability of 5 m/d was selected and a typical porosity for this type of formation would be 0.1. The hydraulic gradient was assumed to be 1/100. The velocity was therefore: (5*0.01)/0.1 = 0.5m/d.

The team used the low-risk travel time (exceeds 25 days) and therefore the required horizontal distance was: 0.5*25 = 12.5 m. Subsequent analysis of the water combined with sanitary inspection confirmed that these distances were effective.

Numerical tools to support siting decisions

Numerical approaches have been developed to determine set-back distances using contaminant transport and groundwater flow models (Bear *et al*., 1992). Commercial software including numerical codes such as MODFLOW (McDonald and Harbaugh, 1988) and FLOWPATH (Franz and Guiguer, 1990) have received widespread application under a variety of hydrogeological conditions (Cleary and Cleary, 1991; Bair and Roadcap, 1992; Taylor and Howard, 1995). A distinct advantage of numerical models is that the impact of varying different factors such as slope (topography) and pumping (abstraction) rate on time of travel can be evaluated thereby enabling estimation of generic set-back distances.

Apart from the necessary expertise, a key detraction to the use of numerical models is that they require a significant range and input of data including many parameters such as hydraulic conductivity and porosity for which there are often significant uncertainties. Furthermore, most models are run under steady-state conditions that assume uniform hydrogeological conditions even for highly dynamic parameters such as recharge and discharge (pumping). Estimation of set-back distances typically presumes that sewage-derived pathogens move at the same rate as groundwater flow and survive for similar lengths of time in groundwater (e.g. 50 days) regardless of water temperature and chemistry. Approaches based solely on travel time do not take into account that distance may also be important in determining microbial removal. Such gross assumptions are, however, common to all methods of estimating set-back distances, which are largely justified on the basis that this will provide protection against gross contamination and may be applied even where data is limited. As noted in Chapter 18, however, the use of single travel times may not be fully protective and leads to a significant residual risk to public health (Schijven *et al.,* 2002a; 2002b). Developing more complex models taking into account all the factors influencing microbial removal may increase the certainty with which set-back distances are defined at a local level, but will require significant data on local hydrogeological conditions. In some situations the limitations of available data may make collection of additional information valuable or even essential in establishing guidelines for siting of on-site sanitation and water sources. There are a number of ways of acquiring this information, including tracer tests, soil percolation tests and targeted water quality studies.

Tracer studies often provide invaluable information regarding specific characteristics of a particular site to aid siting conditions. They may also be used to develop an understanding of aquifer types and can provide useful data regarding regional groundwater flow rates and the likelihood of preferential pathways. When the principal concern is to understand groundwater flow, conservative, non-hazardous chemical tracers can be used (for instance chloride or non-hazardous dyes). Chemical tracers may be of little value when determining whether local conditions will lead to breakthrough of pathogens. If this is of interest, microbial tracers (e.g. bacteriophages; see also Box 17.1 in Chapter 17) will provide a better indication of whether there is likely to be significant attenuation within the environment being studied and thus provide greater information for the siting of on-site sanitation. This may be important when determining whether a significant risk exists from latrines located close to a water source.

Drangert (2000) refers to tracer studies in Kenya that showed where latrine pits reached the saturated zones bacteria travelled 20-30 m within a week and in areas of pronounced topography bacteria could travel distances of up to 100 m within a day. This suggests that in this case, either the water source or sanitation technology should have been changed. By contrast, in tracer studies in Uganda, breakthrough by conservative chemical tracers occurred within 24 hours, whilst no phage tracers were detected over the 120 hour sampling period, suggesting that there was greater protection against microbial contaminants than would be suggested from groundwater flow rates (Taylor *et al*., 2004). Soil percolation tests may also provide some information regarding how rapidly effluent may infiltrate into the soil and this may be used to aid planning of siting and sizing of drainfields and soakaways. These tests will, however, provide very limited information for pit latrines, unless the test is performed at the likely depth of the latrine.

Where there is limited hydrogeological data, the use of well-designed water quality studies can provide information regarding appropriate set-back distances. This may be done by selecting a representative sample of water supplies and undertaking an assessment of water quality over a period of time, combined with detailed assessments of latrine proximity. The assessment should ensure that all seasonal differences will be covered and consideration may need to be given for more frequent sampling during the onset of the rains when water quality often shows greatest deterioration (Howard *et al*., 2002). The best way to analyse this data is to compare latrine distance against water quality targets to determine at which distance the latrines start to exert an influence.

22.3.2 Engineering design to control pollution in high-risk areas

Where pit latrines must be used and risks of aquifer contamination are high, control measures addressing design and construction of the sanitation facilities are important to reduce risk. High-risk areas will include those areas where the water table is high or where there are very rapid groundwater flow rates (for instance fracture aquifers, gravel and aquifers with preferential flow paths).

Where there is limited space between the base of the pit and the water table, the use of sand envelopes around the base and sides of the pit are often recommended as this will help encourage an active biological community to reduce breakthrough of pathogens (Franceys *et al*., 1992). These recommendations are based on original field and laboratory experimentation by Coldwell and Parr (1937) and later by Ziebell *et al*. (1975). The former found that a 0.25 m envelope of sand provided an effective barrier to thermotolerant coliform movement. However, although this provides confidence in control of bacterial contamination, confidence in control of viral pathogens is more limited. Ziebell *et al.* (1975) found that development of biological communities within sand envelopes took up to 100 days, suggesting an initial period of elevated risk during the first use of the latrine.

Whether the use of sand envelopes is economically feasible is questionable, for instance Pickford (1995), commenting on recommendations for a 0.5 m sand envelope in India, notes that this would lead to a four-fold increase in the volume of the excavation of a 1 m diameter pit. In such circumstances using an alternative source of water, treating the water or using an alternative sanitation design may be more cost-effective.

Where water tables are high, the use of dry latrines may be more appropriate than wet latrines, as the latter have significantly greater hydraulic loads which may exceed attenuation potential even when enhanced by the addition of sand envelopes. If wet latrines will be used because of cultural practices or preferences, then siting will be critical and consideration should be given to the use of alternative water supplies or treating existing supplies.

Vault latrines

The risks from on-site sanitation in high water table areas can also be reduced by using vault latrines (also known as cesspits). A vault latrine has a watertight lining on the pit that does not allow significant infiltration into the surrounding soil and which requires periodic emptying (Franceys *et al*., 1992). An example of a vault latrine is shown in Figure 22.2 below.

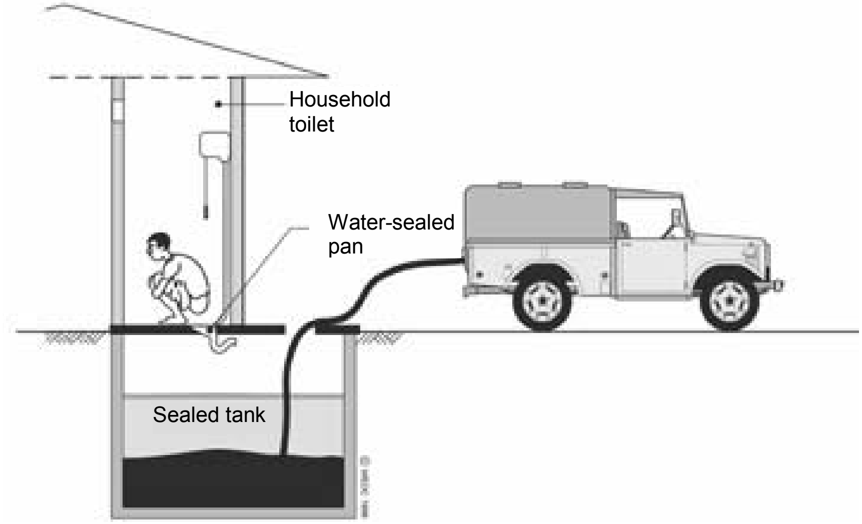

Figure 22.2. Vault latrine

Most designs retain excreta for a short period of time. Because of the volume of liquid collected in the tank, emptying is typically required every two to three weeks. Experience reported from Japan and Korea suggest that vault and vacuum systems are cost-effective and wastes can be managed properly (Pickford, 1995; Ahmed and Rahman, 2000). The use of vault latrines remains limited in many developing countries, primarily because of the high operating costs associated with emptying. Some authors suggest that they are not appropriate as construction and operation are often poor resulting in significant health risks to users and the wider community (Franceys *et al*., 1992). However, designs continue to be developed and tested successfully (Dadie-Amoah and Komba, 2000). Proper construction can be supported by establishing and enforcing construction standards to ensure that vault latrines do not still represent a risk to groundwater. Proper operation, emptying and maintenance at adequate intervals can be supported by a management plan that describes these activities and the responsibilities for them.

A variety of low and high-cost emptiers are available and have been tested. For instance, a programme in the Kibera slum in Nairobi has shown that a small pedestrian-operated tanker (the vacutug) provided an effective service (Wegelin-Schuringa and Coffey, 2000). Similar equipment (the MAPET) was used in Dar-es-Salaam, Tanzania (Howard and Bartram, 1993; Wegelin-Schuringa and Coffey, 2000) and other equipment has been used for pit latrines in Zimbabwe (Jere *et al*., 1995).

The final disposal of sludge should be properly managed. In Kibera, disposal of the sludge is into sewers or direct to sewage treatment works. However, enforcement is often important as previous experience in Dar-es-Salaam showed that there were concerns about burying of the sludge on-site or close to homes, with consequent risks of soil and water contamination and vector breeding problems (Howard and Bartram, 1993).

The lining of the vault pits is often susceptible to damage during the emptying process and it is important to ensure that the power of the suction pump used to empty the pit contents will not cause damage to the linings. Inspections of lining integrity are an important control measure but are difficult to enforce in many settings. They require trained inspectors with appropriate safety procedures, protective clothing and masks.

In some areas of very high water tables, pit latrines are raised to about ground level (Mara, 1996). These are typically expensive to construct and require regular maintenance and, as noted by Franceys *et al*. (1992), care should be taken to avoid seepage of effluent at or above ground level. In some situations mound latrines are constructed with a hole and bung inserted into the pit to allow rapid emptying without the need for suction. This is acceptable if this is designed and operated correctly and has fittings to allow a pipe to be connected to a tanker. In many cases the hole and bung are poorly designed or emptying is done by households simply by opening the bung during in periods of rainfall with the pit contents discharged to the nearest storm water drain. This has been noted to occur, for instance, in low-lying areas of Kampala, Uganda. Such practices represent a significant risk to health, may cause groundwater contamination and should be avoided.

Ecological sanitation

There is increasing interest among some workers in the sanitation and groundwater sector in the use of ecologically sustainable sanitation that promotes the re-cycling of nutrients for use as fertilizers in agriculture or gardening and to avoid water pollution with nitrate and phosphorus. Ecological sanitation as it is commonly known can cover a wide range of technical options from very high to comparatively low cost. The designs can either involve separation of urine or composting and in all cases the reuse of wastes is promoted as a means of ensuring nutrients are recycled in the environment (Drangert, 2000; Winblad, 2000; Esrey, 2001).

The use of on-site methods of eco-san are likely to beneficial in relation to preventing groundwater contamination because they have a low hydraulic load. Although there are many ardent advocates of ecological sanitation, this is not a technology with zero groundwater pollution potential nor does it provide overall greater benefits than alternative options. The final disposal of wastes may still lead to problems if it is not managed properly; and the use of organic fertilizers does not mean, for instance, an immediate removal of problems with nitrate contamination. The disposal of wastes may be more problematic in urban areas where there may be more limited local demand for use in agriculture, leading to poor disposal methods and public health risks.

There is also concern regarding the safety of handling the matter and ensuring that there has been inactivation of pathogens. Of particular importance is not whether recommended practices limit such risks, but actual practice by the users in relation to their exposure to raw or poorly treated faecal material.

22.4 MEASURES FOR CONTROLLING RISKS FROM SEPTIC TANKS AND AQUAPRIVIES

A key element in both septic tanks and aquaprivies is that the tanks should be watertight to prevent subsurface leaching of contaminants into groundwater. Groundwater contamination tends to result from infiltration of effluent through drainfields, trenches and pits, the density of septic tanks in an area or poor siting in relation to vulnerable groundwater sources (Payne and Butler, 1993).

The control of the location and density of septic tanks involves ensuring that planning and development legislation takes due account of the groundwater protection needs. Payne and Butler (1993) provide a series of simple flow charts to aid planners in the United Kingdom decide whether applications for septic tank construction should be approved.

As septic tanks and aquaprivies must be emptied periodically, control of the final sludge is essential. Uncontrolled, illegal emptying or dumping of sludge into the environment may represent a significant risk to groundwater. One form of control is through the licensing of de-sludging companies and enforcing codes of practice. Management plans defining these operations, responsibilities and documentation of emptying may support good practice and surveillance.

Legislation should also include penalties for households that illegally empty their tank, although the monitoring of this may present some difficulties.

Effluents are most often disposed of through a soakaway or drainfield containing infiltration trenches (Franceys *et al.*, 1992). Soakaways require less space but infiltration trenches have several advantages, such as increased area for infiltration (through the sides of the trench), the potential for shallower construction (increasing the travel path to any underlying aquifer) and the ability to distribute flows along the trench, providing alternative infiltration routes, unlike small soakaways which may eventually become clogged. Soakaways may be either underground chambers with openings in the base and sides to allow infiltration to the soil or an underground pit filled with coarse granular material, often lined with a geotextile to prevent ingress of silt. Where underground chambers are used, surrounding the structure with sand may provide additional potential for the removal of pathogens.

Infiltration trenches are normally filled with coarse granular material with a perforated pipe in the base of the trench to distribute the effluent along it, avoiding overloading the soil at any one particular point. Designs for drain trenches should take into account infiltration rates, which should preferably be calculated on-site, but the values in Table 22.2 can be used as a general guide.

Table 22.2. Infiltration capacity of different soil types (based on Franceys *et al.*, 1992)

Type of soil	**Infiltration capacity – settled sewage (l per m^2 per day)**
Coarse or medium sand	50
Fine sand, loamy sand	33
Sandy loam, loam	25
Porous silty clay and porous clay loam	20
Compact silty loam, compact silty clay loam and non-expansive clay	10
Expansive clay	<10

The performance of the drainage trenches depends on the efficiency of the tank and soil conditions and some workers suggest separating sullage from toilet wastes and treating this separately (Franceys *et al.*, 1992). Alternatively the performance of the septic tank or aqua privy can be enhanced by extending the treatment process through increasing the size of the tank and introducing baffles to promote sedimentation.

22.5 MEASURES FOR PREVENTION AND CONTROL OF SEWER LEAKAGE

The easiest, cheapest, most straightforward way to manage pollution from sewers is to not let it happen in the first place. Misstear *et al.* (1996) note that leaks from sewers arise from a combination of:

- cracked and fractured pipes
- opened or displaced pipe joints
- root intrusion
- pipe deformation
- sewer collapse
- reverse gradients
- siltation
- blockages
- poorly constructed connections
- abandoned laterals left unsealed.

These may be due to ground loss, ground movement, material deterioration or poor system management. Control measures to protect groundwater from sewer leakage therefore include planning, design and construction as well as maintenance and operational controls.

The design of the sewerage system can reduce risks of leakage. Good workmanship, careful inspection of the pipes while they are being laid, the use of good quality pipe and bedding materials and careful compaction all improve the life and physical condition of the pipe. Testing the pipes after they have been laid can identify poor construction practices. Using shorter 'rocker' pipes in areas where there might be settlement allows the pipes to move rather than crack.

Pipes and pipe bridges on or above the ground need to be protected against physical damage, e.g. from accidental collisions. Burying the pipe gives a degree of protection and support. A compromise has to be made between giving the pipe sufficient cover to protect it from surface loading and burying it deeply which makes the sewer more difficult to monitor and replace, and which reduces the travel time of any leaks to the aquifer. In areas where a shallow buried pipe may be subject to damage because of heavy loads passing over the sewer route, the bedding can be replaced with concrete (either just below the pipe or completely encasing it). Routing the pipes in areas where they will not be subject to heavy loads will also increase their robustness.

If the surrounding ground is relatively impermeable, the bedding material in the pipe trench itself can become a drainage route for any leakage, especially if the pipes are laid on a slope. Placing a clay collar around the pipe can prevent the flow of wastewater along the pipe route, as shown in Figure 22.3.

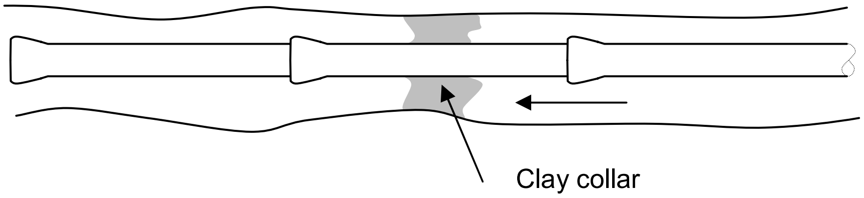

Figure 22.3. Clay collar on sewer

22.5.1 Sewer management

Ensuring that sewers do not become surcharged (i.e. flow full) reduces the possibility of sewage leaking out of the pipe. This can be achieved by ensuring the pipe is large enough for future flows, having separate pipes for surface water drainage, periodically cleaning pipes, monitoring pipes for blockages and removing them promptly, and public education, to prevent unsuitable objects being introduced into the sewer.

Ensuring that connections are made to the pipe either at manholes or using specific lateral connection pipes is preferable to using pipe saddles to connect to existing pipes, as these are more prone to leakage. Where connections are no longer required, these need to be plugged to prevent leakage.

Action can also be taken on what goes down the sewer. Charging for industrial waste can encourage users to reduce the amount of wastewater they produce or cause them to pre-treat the effluent before it enters the sewer. Some substances can be banned from being disposed of into sewers. This action will depend on a working regulatory system.

Hydrogen sulphide formation can represent a significant problem for sewers, leading to conversion to sulphuric acid which can cause corrosion of sewer pipes. Hydrogen sulphide can also lead to odour problems. Metcalf and Eddy (1991) note that hydrogen sulphide attack can be controlled by:

- controlling organic and sulphur inputs at source
- aerating the sewage
- adding chemicals
- periodic cleaning
- ventilation
- good design.

Routines for sewer management, such as monitoring for leaks and blockages, cleaning and maintenance, responsibilities and documentation are best laid down in management plans.

22.5.2 Controlling exfiltration

If exfiltration is suspected, temporary or permanent sumps can be dug into the pipe bedding to collect any leakage and monitor changes in flows. Trying to monitor flows at the end of the pipe would necessitate careful planning, as the complex and changing relationship between sewer inflows, infiltration, exfiltration and overflows can make firm conclusions difficult to arrive at. Large rises in flows during wet weather can indicate infiltration to a foul sewer or misconnections from storm water sewers, as can high night-time flows that do not correspond to water consumption.

Visual surface inspections of the sewer route may reveal major leaks (especially in a dry season) whilst a CCTV survey can give a more detailed analysis. New developments are bringing in lasers and ultrasound to improve inspection, especially below the water flowing in a live sewer (Makar, 1999). Such inspection techniques however are expensive and only provide a snapshot of the state of the sewer. CCTV and other such methods are not suitable for the small diameter pipes used in condominal sewerage systems. Flow measurements can be made at successive points along a sewer line. Assuming no inflows, an assessment can be made of leakage from the sewer. This may vary with seasons.

For public sewers possible strategies are the adoption of a double skin construction technique (although this may not prove cost effective) and the adoption of higher testing pressures. It is also important to include private sewers in a regular schedule of sewer testing especially in areas of high groundwater vulnerability. Misstear *et al.* (1996) recommend installation of shallow monitoring boreholes in environmentally vulnerable areas perceived to be at risk, as well as improved monitoring of the water supply boreholes themselves, measuring microbial indicators, nitrogen species, boron and phosphate.

22.5.3 Control of sewer leakage

If sewers are found to be leaking, but the pipes are still structurally sound, there are alternatives to replacing large amounts of the system. These include relining the pipes – either through spraying a cement coating onto the inside of the pipe or by inserting a flexible plastic liner into the pipe that can then be fixed to the walls. Localized leaks (from cracks or failed joints) can be grouted remotely to seal the hole. Where pipes are no longer structurally sound, the existing pipes can be burst and replaced with a new plastic pipe without having to dig a new trench.

22.5.4 Open drains

Sewers are not just limited to pipes below ground. Open channels may also be used. These may be unlined, pitched with stone or lined with concrete. Where the lining is not water tight, the channel can act as an infiltration trench. This may be acceptable for surface run-off, but is not recommended for conveyance of foul sewage. Surface run-off can flood the channel, causing pollution, which is a greater risk to health than the indirect route of infiltration to groundwater. Where open channels are used for foul sewage and no alternative is possible, they should be routed away from populated areas and have raised sides to limit the ingress of rainwater.

22.5.5 Surface water management

Whilst rainwater is perceived as being clean it can rapidly become polluted and transport contaminants, for example washing poorly disposed faeces into the water cycle. Flooding can cause sewer surcharge and inundate pit latrines. Therefore attention needs to be paid to the management and disposal of stormwater, as soakaways and ponds may provide a path for contaminants to the aquifer. CIRIA (2000) provides an indication of methods used to manage storm water run-off depending on the land use of the catchment and the status of the groundwater.

22.6 CONTROL MEASURES FOR SEWAGE TREATMENT

Where sewerage systems exist they need to be connected to some form of sewage treatment and disposal which protects public health from exposure both directly and through contaminating groundwater. Options range from conventional plants over alternative systems such as waste stabilization ponds and wetland systems. The use of excreta and wastewater may be a desirable option, but may also represent both a direct risk to health and a risk of groundwater contamination (WHO, 1989; Foster *et al.*, 1994; Mara, 1997). Planning and designing wastewater and excreta use should therefore relate to aquifer vulnerability. One control measure is banning or restricting wastewater irrigation within drinking-water protection zones, unless the quality of the treated wastewater is sufficient as to represent little or no risk. Controls in application and means of irrigation and use of fish ponds are discussed in Chapter 21.

22.6.1 Conventional treatment works

Sewage treatment plant outfalls chiefly pollute surface waters. Risks to groundwater will derive from the final disposal of the sludge and its location with regard to groundwater, as well as from hydraulic connections between groundwater and surface waters affected by sewage. Leaking sewage pipes can also contaminate groundwater sources.

Sludge disposal to land or landfill is widely practised and in many countries is subject to specific regulations governing acceptable practice. These will usually govern the conditions under which different types of sludge (untreated, partially treated, treated) can be disposed of and set allowable concentrations of contaminants in sludge quality guidelines and water quality objectives (WRc, 1992; US EPA, 1995a; 1995b). The risk to groundwater from land application of sludge is generally related to aquifer vulnerability and is considered to be particularly relevant to applications close to a groundwater abstraction point (Wolstenholme *et al.*, 1992) (see also Chapter 21).

Various tools have been developed to aid decision-making based on regulations. For instance in South Africa, an expert system for use in sewage sludge has been developed called Sludge Land Application Decision Support which aids decision-makers in establishing sludge disposal guidelines (Anonymous, 1997). This requires significant amounts of data on contaminant loads as well as soil and groundwater conditions. Similar guidance has been developed by the US EPA (1995a; 1995b) which provide detailed discussion of the site conditions with respect to sludge type and quality, soil and hydrogeology.

The development of site-specific plans is essential for effective management of sludge. In general, sludge disposal to land should not occur within an area where groundwater is (or needs to be) protected against microbial contaminants, and sludge disposal to land in areas protected against nitrate contamination should also be restricted.

For effluents, quality control will be achieved through application of appropriate discharge consents and water quality objectives for receiving waters, which will typically be set taking into account uses of the water (including environmental/ecological demands). This should also take into account the nature of surface water-groundwater relationships and in particular to ensure that in situations where surface water recharges groundwater, the potential for groundwater pollution is addressed.

Sewage discharges into surface waters that recharge groundwater should be controlled and discharge consents applied that will be consistent with the protection of groundwater quality. This often results in the extension of groundwater protection zones for significant distances along rivers upstream of abstraction points.

22.6.2 Waste stabilization ponds and reedbeds

Waste stabilization ponds are widely used in developing countries, but are also used in industrialized countries where there is sufficient land available (Horan, 1990; Mara, 1997). Waste stabilization pond systems are usually composed of a series of ponds with sludge treatment carried out in the first pond (which may be anaerobic or facultative), subsequent treatment through secondary facultative ponds (taking settled sewage) and a series of maturation ponds. Well-operated waste stabilization ponds produce very high quality effluent that should represent limited risk to health when discharged and often represent significantly lower operating costs than alternatives (Mara, 1997).

The risks to groundwater from waste stabilization ponds arise primarily from the risks of leaching of wastewater from the base of the ponds leading to microbial or chemical (particularly nitrate) contamination of underlying groundwater. The base of waste stabilization ponds are normally compacted to provide an aquitard layer to ensure the pond will fill with water and to prevent leakage into the subsurface. A specific lining is often also installed; conventional approaches use a puddled clay layer of 5-10 cm thickness, although polyethylene and vinyl sheeting have been used in smaller ponds (WHO-EMRO, 1987).

Although some experts believe the risk to groundwater is be restricted solely to those situations when ponds are located close to abstraction points, infiltration of up to 20 mm per day from ponds has been noted to occur in Latin America and the Caribbean (Foster *et al*., 1993). In Lima, Peru, penetration of indicator bacteria beneath waste stabilization ponds of over 15 m has been noted, although the majority of microorganisms were removed in the top 3 m of the unsaturated zone (Geake *et al*., 1986). This indicates the need for proper site investigations and ensuring that ponds are not located over significant aquifers used for domestic water supply.

Reedbeds are also used to treat effluent prior to discharge and can provide significant improvements in wastewater quality. The major problem for groundwater will be leaching of contaminants into the sub-surface, and studies on this issue are limited. Contamination may be significant when the wetland is influent to groundwater, but limited when the groundwater is influent to the wetland. The risk to groundwater can be controlled by locating reedbeds with sufficient distance to abstraction points.

22.7 MONITORING AND VERIFICATION OF MEASURES CONTROLLING SANITATION SYSTEMS

Measures for controlling human excreta disposal and sewerage in drinking-water catchments proposed above range from planning the choice of site and sanitation technology in relation to aquifer vulnerability and socioeconomic criteria to specific design and construction criteria for sanitation facilities and operational controls. Selected examples are summarized below in Table 22.3. Where drinking-water supply and sanitation are a joint responsibility of a utility or community, such measures may readily be integrated into a WSP.

NOTE ▶ *The implementation of control measures such as those suggested in Table 22.3 is effectively supported if the stakeholders involved collaboratively develop management plans that define the control measures and how their performance is monitored, which corrective action should be taken both during normal operations and during incident conditions, responsibilities, lines of communication as well as documentation procedures.*

The implementation of control measures protecting drinking-water aquifers from industry, mining and military activities is substantially facilitated by an environmental policy framework (see Chapter 20).

Supporting programmes specifically for protecting groundwater from human excreta may include but are not restricted to the development of guidance on sanitation technology selection, ensuring that construction quality standards are developed and enforced, and community education regarding items and substances disposed of in sewers and latrines.

Monitoring and verification of the control measures implemented is crucial to ensure that they are in place and are effective. Table 22.3 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. In the context of planning, surveillance will address whether plans exist and how they took criteria for siting and set-back distances in relationship to aquifer vulnerability into account. Verification will address whether these criteria are being adhered to and plans are being implemented, e.g. by site inspection to check the location of sanitary facilities and the depths of pits and sewers during their construction.

Once the planning stage has determined safe site selection and sanitation facilities, monitoring their design and construction is important to ascertain their integrity, e.g. whether latrine pits are fitted with liners or sewer pipes with clay collars. For the day-to-day routine operation of control measures, monitoring focuses on assessing whether they are functioning as they should, e.g. whether sewers or pits are leaking, whether latrines are in a condition to be used and whether sewage sludge is disposed of as approved by the permit (see Table 23.1). This can in part be achieved through inspection, and defining inspection routines in management plans is useful to support that they are regularly performed. Monitoring for leaks often requires analysing a selected parameter in groundwater near the respective sanitation facility (e.g. latrine pit or sewer) which will most effectively indicate leaks. This may be achieved with indicator organisms (e.g. faecal streptococci, *E. coli*, bacteriophages) or substances typically present in the sewage. Where sewerage is contaminated by a range of chemicals from household use and connected enterprises, monitoring overall groundwater safety would occasionally address these contaminants. This also applies to sludge contaminants of specific concern where it is applied on land.

Management plans will define monitoring systems, corrective action to be taken if leaks are detected as well as regular maintenance operations. To be effective, they include responsibilities and routines for documentation of these activities, their findings and any corrective action taken.

NOTE ▶ *Options for monitoring suggested in Table 22.3 focus on the control measures rather than on groundwater quality. Analysis of selected parameters in groundwater which indicate leaks of on-site or sewer systems 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 the overall drinking-water catchment management.

Table 22.3. Examples of control measures for sanitation systems and options for their monitoring and verification

Process step	Examples of control measures for sanitation systems	Options for their monitoring and verification
PLANNING	Require set-back distances for sanitation facilities in relation to travel time to aquifer, as adequate in local hydrogeological conditions Locate sewers outside drinking-water protection zones Ensure sufficient distance (at least 2 m) between base of latrine pit, soakaway or infiltration trench and highest water table	Review (applications for) permits for construction of new on-site sanitation systems or sewers Inspect protection zones to ensure that set-back distances are implemented Inspect sewer laying and pit construction to verify that safe distances are implemented Conduct tests with tracers and/or indicator organisms to verify adequate siting
	Require permits for sludge disposal or reuse options based on an assessment of aquifer vulnerability and contaminants	Review (applications for) permits for sludge disposal Conduct tests with tracers and/or indicator organisms to verify safety
DESIGN AND CONSTRUCTION	Construct and maintain vault latrine pits impermeable Fit sewers with linings to reduce breakage Fit waste stabilization ponds with linings	Inspect during construction Carry out tracer tests Monitor selected groundwater parameters (indicator organisms, substances typically occurring in the sewage) which would indicate leakage
OPERATION AND MAINTENANCE	Maintain on-site sanitation facilities in good condition and encourage use	Inspect regularly
	Maintain condition of clay collars on sewers	Inspect regularly
	Prevent sewer leakage	Run sewer leak detection programmes Review records of sewer leak detection and repairs
	Implement adequate final disposal of sludge as designated	Inspect disposal practices

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23

Industry, mining and military sites: Control and protection

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A range of hazardous substances may be released to the environment from industrial sites, depending on specific industrial processes (see Table 11.2). Among these, the mobile compounds reach groundwater (see Chapter 4). Less mobile compounds may also contaminate groundwater where process wastewaters are discharged through soakage pits. The most common contaminants to reach groundwater in significant quantities from industrial sites are the chlorinated solvents such as trichloroethene (TCE) and perchloroethylene/tetrachloroethene (PCE) but, in specific circumstances, concentrations of many others such as chromium and petroleum constituents may be elevated. Mining can give rise to a range of inorganic contaminants and acid waters, in particular, can result in the accelerated leaching of metals into groundwater. Stored, disposed and deteriorating explosives have been found in some groundwaters below military sites. In Germany and in the USA, perchlorate used in rocket fuel has given rise to major problems. However, the most common contaminant for both military and industrial sites is probably oil from machinery and vehicles, particularly in the case of military sites.

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In contrast to groundwater contamination from agriculture and off-site sanitation, larger industrial operations tend to be localized point sources of pollution. This is not the case for small-scale enterprises, particularly where these are not connected to centralized sewerage. Nevertheless, the control and protection measures proposed in this chapter for industry can in principle be applied to small-scale enterprises as well.

Military bases often resemble both industrial facilities and small cities regarding the use, storage, and disposal of a variety of chemicals, heavy metals and waste materials. Many planning and operational control measures to prevent the contamination of groundwater by chemicals used in routine military operation are the same as those for industrial sites, and they are therefore discussed together in this chapter.

A variety of effective control measures can be implemented to minimize the likelihood and the magnitude of groundwater impacts from industrial, mining and military activities in groundwater recharge zones. These measures fall into broad categories of: (i) planning, including principal site selection; (ii) engineering approaches which can be implemented in the phase of planning and designing of facilities; and (iii) operational/procedural controls which can be administrated for both new and existing facilities. Some control measures may have both engineering implications (process design) and administrative elements (modification of employee practices), e.g. efforts to substitute with less hazardous process chemicals or development of a corporate recycling plan to reduce waste volumes. Operational monitoring of control measures is important to ensure the ongoing safe storage, handling and disposal of process chemicals, maintenance supplies and waste materials (see Table 23.1). Good practice to support this includes training of personnel in proper safety and handling of these materials under routine conditions as well as in the case of spills or leaks.

All of these measures are typically directed at preventing or limiting the quantity and significance of releases. They include monitoring for early detection of releases and improvement of available containment or remedial capabilities in the event that accidental or intentional contaminant releases occur. In terms of resource allocation, there is a clear benefit to avoidance of releases or accidents. Plans and procedures for avoidance of releases are usually less costly in terms of time and money than remedial measures (i.e. the cleanup of contaminated media such as soils and groundwater) once contamination has spread over a broader area, perhaps even throughout a watershed or aquifer.

Implementing control measures for industry, mining and military sites in drinking-water catchments can be triggered by water suppliers and/or the public authority responsible for drinking-water safety, e.g. in the context of designating protection zones (see Chapter 17), or in the context of developing a WSP (see Chapter 16).

NOTE ▶ *In developing a Water Safety Plan (Chapter 16), system assessment would review the efficacy of control measures and management plans for protecting groundwater in the drinking-water catchment from contamination by industrial, mining and military activities. Chapter 11 provides the background information about the potential impact of these activities on groundwater and provides guidance on the information needed to analyse these hazards.*

This chapter introduces options for controlling risks from these activities. As the responsibility for them usually falls outside that of drinking-water suppliers, close collaboration of the stakeholders involved, including the authorities responsible for the surveillance of industry, mining and military activities, is important to implement, upgrade and monitor these control measures. This may be initiated by the drinking-water sector, e.g. in the context of developing a Water Safety Plan or of designating protection zones (see Chapter 17).

23.1 INDUSTRIAL AND MILITARY SITES

As discussed in Chapter 11, the main concern at industrial facilities as well as at smaller enterprises typically is the improper containment and handling, management or disposal of chemicals, which can lead to soil, surface water and groundwater contamination. This may be the result of active contamination routes, such as intentional dumping or inappropriate disposal activities, or may occur via passive contamination routes such as leaking tanks or broken transfer pipes. Both for industrial and for military sites, groundwater protection usually involves improvement of design and construction of facilities, modification of current practices, as well as remediation of past contamination.

23.1.1 Strategies for pollution prevention and environmental management

The protection of groundwater from industrial and military contaminants is facilitated if this can be managed within general environmental controls, i.e. in environmental management systems such the international ISO 14001 standard or pursuant to EU Regulation 761/2001. One example of a comprehensive strategy to address site-specific control measures at industrial facilities is embodied in the 1991 Integrated Pollution Prevention and Control approach of the Organisation for Economic Co-Operation and Development in Europe (Recommendation on Integrated Pollution Prevention and Control; C/90/164/Final/ 1991). This approach recommends means by which to anticipate and manage chemical handling and process-related activities that may potentially contaminate the environment, including groundwater. Recommendations include those of an engineering nature, as well as an administrative or institutional nature. The approach calls for:

- identification of existing contamination;
- design of mechanisms to detect potential future releases;
- development of plans to minimize the impacts of such releases.

Various cradle-to-grave or catchment-to-consumer management strategies similar to the Organisation for Economic Co-Operation and Development approach for chemicals, especially directed at protection of groundwater resources, have been implemented in a number of countries. Such management systems help to achieve the objective of establishing environmentally safe and groundwater-conserving practices in dealing with industrial chemicals through policy and administrative measures as well as through an appropriate management of material flows based on life cycle analysis. Active military installations, for example, are well suited for such management systems due to the controlled nature of site personnel and activities. Environmental management systems can, in the long term, replace some monitoring and control tasks, resulting in cost saving.

Audits and evaluations of products are one way in which manufacturers, distributors and users of chemicals can contribute to production and use of substances with less pollution potential (HERA, 2002). Environmental and regulatory compliance audits have been common practice in industrial and commercial settings for a decade or more under international programs of environmental management and consumer product safety such as ISO 14000 (Fredericks and McCallum, 1995; ISO, 2001). In addition, responsible and detailed labelling of consumer products is a method for linking information from the manufacturers with consumers and users to optimize environmentally sound disposal practices (US EPA, 2002b).

Similarly, the encouragement or institution of procedures for re-using waste materials can be an economically and technically sound means to reduce waste volumes and limit potential contamination by process wastes. The use of internal process modifications, or business contacts with an external waste exchange programme which converts one plant’s waste output into another plant’s resources are proven methods for achieving these goals. Industrial waste treatment and recovery strategies to convert or to process wastes into profitable materials have been effective in worldwide applications since at least the 1970s. These strategies are most effective where large volume wastes of specific types (e.g. spent solvents with low residual contaminants) are available from a plant, and low cost transportation is available to a plant with distillation or purification facilities.

Waste exchange, defined as the use of discarded, surplus or off-specification materials for beneficial purposes, represents one potential component of waste management options. While some materials are easily amenable to such exchanges (e.g. solvents for reclamation, metals dusts for refining), other waste sources require innovative approaches to identify users. Examples such as the oil refinery in Poland discussed in Box 23.1 illustrate the double benefit associated with the waste exchange concept. This growing trend in waste management benefits both parties and is typically facilitated by a non-profit intermediary.

Box 23.1. Waste exchange at a petroleum refinery site in Czechowice, Poland

The oil refinery case example described in Chapter 11 (Box 11.1) illustrates the potential for waste exchange as an avoidance strategy: Final disposition of the acidic petroleum sludges currently stored in the refinery's waste lagoons is an issue of concern for the refinery as it seeks to modernize its operations. With advice and guidance from an American waste exchange, the refinery sought to find a potential user for these sludges. A nearby cement manufacturer was identified as having the capabilities to co-fire the sludge in their cement curing/drying kilns, strictly for its energy value. Negotiations between the two parties led to a series of test burns using varying amounts of refinery sludge. The process was proven to be feasible and negotiations began for full-scale implementation. Successful consummation of this arrangement provided a low- or no-cost source of supplemental fuel to the cement manufacturer while providing a disposal mechanism and, potentially, income to the oil refinery. Existing waste materials will be removed from the urban area in which the refinery is located, reducing the potential for groundwater contamination, and the cement manufacturer will reduce their use of external fuel.

A further important strategy to avoid contaminating groundwater is transition to production processes that substantially reduce or totally replace the use of hazardous chemicals and/or the use of water. Such developments have been successful in many branches of production and include effluent-free steel industry, mercury free chlor-alkali electrolysis, AOX-free propendioxide production, or wastewaterless flue gas washers and cooling systems. Instalment of such production technologies often proves cost-effective for the enterprise within fairly short time spans, particularly in settings where water prices are an issue, or where the enforcement of pollution restriction legislation renders polluting practices costly.

Avoidance strategies are also important for a wide variety of substances used in industry and with the potential to adversely affect groundwater which are also are present in common household products (e.g. alcohols, petroleum hydrocarbons, chlorinated solvents, soaps/surfactants, ammonia, phthalates, paints, batteries, pesticides, adhesives). While individual quantities per household may seem small in comparison to those generated by industrial facilities, a large number of households disposing such products in landfills and/or septic systems may represent an equal or greater potential hazard (EC, 2002; Health Canada, 2002; US EPA, 2002a). In some areas, incentives encourage the production, marketing and use of less toxic and less environmentally hazardous alternatives. However, the costs and time necessary to effect changes in established behaviours can be large (EC, 2002).

23.1.2 Choice of site

A fundamental element of any strategy for prevention or avoidance of adverse impacts in groundwater recharge areas is appropriate choice of the site for a facility, including the option of relocating existing facilities. Consideration of groundwater vulnerability is invaluable in assessing the suitability of locations for new operations, and may be used in conjunction with site development plans and engineering precautions to design a facility with minimum potential aquifer impacts. An important measure in planning and choice of site is to require permits for construction and operation which specify activities, production processes and management plans. Legislation and local land use controls or zoning requirements can be effective tools to guide industrial development for achievement of minimum impact in drinking-water catchment areas. Limitations on siting in flood prone or low areas, areas of karstic terrain, close proximity to water bodies or within current or potential future drinking-water protection zones recognize that accidental releases or ongoing industrial operations in these areas rapidly affect groundwater.

Where facilities already exist in vulnerable drinking-water catchments and relocation is not an option, control measures to prevent releases of hazardous substances become particularly important, and specific controls may be required in permits for their operation to limit their hazard potential. Such requirements may include use of environmentally improved technology and products, more intensive monitoring systems, emergency response plans and prohibiting the use of specifically identified hazardous substances in their processes.

Issues of site-specific relevance include: surface topography and features; soil type and local variability; aquifer vulnerability (see Chapter 8); proximity to rivers and other water bodies; chemical type, physical form and quantity of materials handled; degree to which plant construction will require major changes to existing conditions and thus impact on aquifer vulnerability (e.g. extensive excavation, backfilling or soil relocation, pipeline installation, well construction, paving or building cover for substantial areas).

23.1.3 Design and construction for prevention of spills and leakage

A wide range of engineering measures can be applied in the design and construction of a facility as an effective defence to prevent or avoid releases of hazardous substances. These include approaches such as impermeable surfaces and secondary containment structures around tanks, double-walled pipes, alarm devices indicating overfilling of tanks or other vessels, and knock-down barriers to protect tanks or pipes from damage by vehicles (see also Box 23.2 for examples). They also include using natural (e.g. clay) or synthetic (e.g. geotextile) liners to prevent percolation from ponds or storage areas, and capturing in-plant process residues or surface run-off in properly designed and constructed holding areas prior to treatment. Often, structures to retain spilled and/or leaking fluids are important particularly for unloading stations where hazardous fluids are transferred from railway or truck tanks to on-site containers (see Figure 23.4 in Box 23.2). Prevention and mitigation of releases can also be accomplished by neutralizing, encapsulating, stabilizing or solidifying materials (e.g. process wastes, soils, sludges) to prevent or control mobility.

Canopies over stored materials, coupled with capping options designed to isolate materials or to protect them from precipitation and to prevent leaching, can also be site-specific source control measures (Figure 23.3 in Box 23.2). The appropriate degree of complexity for a capping option is related to factors including size and configuration of the capped area, toxicity and potential mobility of the materials to be addressed, duration of required isolation, and whether the surface of the capped area is to be used for secondary activities. As indicated in Table 23.1 at the end of this chapter, capping typically will be accompanied by an operational monitoring requirement to ensure that the cap (and/or companion liner system) continues to be effective at isolating the materials. Available capping options vary widely in cost, durability and effectiveness for particular applications. Such options may best be viewed as temporary, albeit long-term, solutions for which subsequent, permanent solutions are desirable.

Levels of sophistication – and thus of costs – can vary for design and construction control measures. Often, fairly simple low-cost measures effectively provide substantial protection against soil and groundwater contamination, and are valuable first steps upon which incremental improvements can build later. In the study shown in Box 23.2, short-term, medium-term and long-term measures were proposed for many of the problems identified. For example, while the long-term measure for protecting tanks against overflow of hazardous chemicals through overfilling would be to fit them with approved devices, overflow can already be quite effectively prevented by installing a simple indicator of filling level and a routine for its regular monitoring. An immediate measure would be to ensure that special care is taken when filling the tank by requiring two staff members to fill the tank together. Likewise, while double bottoms for tanks may be installed in the long run, intensified internal checks and determination of the wall thickness of the tank may improve safety in the meantime.

For all containment structures, regular maintenance and monitoring of their integrity is critical for keeping them functional. Management plans for a facility should include these activities and responsibilities for their regular performance and documentation.

23.1.4 Operational controls

For protecting groundwater from industrial contamination, controlling operations that may lead to spills and leaching is often equally important as safe containment. Operational controls address procedures for handling, using, transferring and storing substances such as properly unloading trucks or railway tankers, using safety couplings and valves, using mobile drip trays, avoiding overfilling containers and providing materials to absorb hazardous chemicals in case of spills. An important aspect is preventing joint storage of substances that may undergo chemical reactions with each other and taking properties such as auto-ignition, combustibility or corrosiveness into account. Also, labelling of tanks, containers and facilities with hazardous chemicals is necessary to allow appropriate emergency responses. A further important operational control is the implementation of emergency response plans which are regularly rehearsed by the staff of the facility.

Operational controls are best developed with operational staff and fixed in writing as standard operating procedures in a facility's management plans. Implementation is supported by checklists and forms to sign after conducting specific routines. Adequate training and qualification of staff, including the aspects of groundwater protection, as well as clear assignment of tasks and responsibilities, are prerequisites to making them work. Often the target of avoiding spills for the sake of groundwater protection is closely linked to the target of avoiding exposure for the sake of occupational health and safety, and both may be addressed within the same control measure.

Box 23.2. Technology transfer for plant-related water protection in Moldavia, Rumania and Ukraine (based on FEA, 2002)

Within the framework of the Environmental Action Program for Central and Eastern Europe which was agreed by the Ministers for Environment of the UNECE, a Technical Assistance Programme launched by the German Ministry of Environment developed a methodology for assessing water pollution hazards by industries with high water pollution potential. This used the recommendations of the International Commissions for the Protection of the Rhine (ICPR) as well as of the Elbe (ICPE) as a basis. From this assessment, short, medium, and long-term measures were identified with which the ICPR and ICPE recommendations can be met. The majority of these measures are equally relevant to the protection of groundwater and surface water. Measures relating to design and structure of facilities include the following:

Short-term measures:

- Repair and seal cracks and damage in existing sealed surfaces
- Perform internal examinations of tanks and containers
- Fill tanks and containers under the supervision of two operating persons
- Examine and prepare a concept for joint storage of hazardous substances (with the potential to react)
- Use mobile collecting basins and detachable connections for plants with transhipment (tank wagon – plant connections)

Medium-term measures:

- Provide a stop valve for open-air collecting basins connected to the wastewater system
- Demonstrate that wastewater pipelines are not leaking (Figure 23.2)
- Renovate sealed surfaces in plants for transhipment and/or storage

Long-term measures:

- Install overfill safety systems for storage containers
- Provide collecting basins for retaining water-polluting substances and fire-fighting water
- Create sealed surfaces and retaining volume for railway tank-car stations (Figure 23.4)
- Establish wastewater treatment facilities that meet quality requirements

Operational control measures include requiring the plant operator to:

- define in-plant responsibilities for taking and checking safety measures which include functional safety, impermeability of containment structures, functionning of safety equipment, documentation (in writing) of regular checks undertaken
- provide detailed reports on accidents and incidents, including causes, consequences and future preventive measures
- report releases of hazardous substances to competent authority
- define equipment for plant monitoring and related instructions for action, including prevention of accidents, water hazard potential, potential for substance release, precautionary measures and protection requirements

- use internal monitoring wherever there is a need to prevent releases of substances hazardous to water, to allow detection on time to implement contingency measures

Checklists were developed for setting up internal alarm and hazard control plans defining actions and responsibilities for types of incidents (e.g. leakage, overfilling of vessels, failures of receptacles, containers, pipelines, fires and fire-fighting water, accidents during transport of hazardous goods) as well as for different plants. This includes exercises to train accident responses at regular intervals.

Figure 23.1. Leakages at a production plant

Action proposals: Technical structures to minimize foaming; venting on a buffer tank for the retention of the foam.

Figure 23.2. Single wall pipe subways through retention room; no knock-down protection

Action proposals: Pipe installation above the retention room wall; constructing knock-down protection (big stones); regular pressure tests; street crossing over ground; double wall pipes installation.

Figure 23.3. Storage of solids

Action proposals: Creation of a reasonable canopy; moving the pipe in the bow area; renovation of the existing sealing area.

Figure 23.4. Unloading station for hazardous fluids from railroad tank cars

Action proposals: Conduct unloading with two people; build adequately sealed retention space.

23.1.5 Decommissioning of contaminated sites

When industrial and military sites are abandoned, hazardous chemicals that may leak into groundwater may unintentionally be left behind. An important control measure in drinking-water catchments therefore is proper decommissioning – potentially involving clean-up – of such sites. Issues of decontamination and remediation of sites formerly used for industrial or military purposes are often complex due to the difficulties of identifying those responsible for the pollution in order to implement the polluter pays principle. This is particularly difficult in the context of abandoned sites. Teaf (1995) and Herndon *et al*. (1995) have described the former military facilities in central and eastern Europe as a large scale example of this and reported that the technical and financial responsibility for mitigation became the burden of the host country. Similar problems occur on abandoned industrial sites. An important control measure to prevent this type of situation is to include the responsibility for decommissioning and potentially necessary remediation in plans and permits for establishing such operations.

23.1.6 Clean-up and remediation of contamination

Once a decision has been made to clean up a given site, an initial site characterization must be performed to determine the type and extent of contamination, it may be possible to use available data for preliminary decision-making. For example, after-care measures in the form of exploratory investigations, containment techniques and remedial actions (Teaf, 1995) were carried out in particular in the early 1990s in Germany for military-contaminated sites located in the vicinity of drinking-water abstraction. This included the toxicological assessment of individual constituents and groups of military chemicals, as well as assessment of their migration behaviour and biochemical, chemical and hydrolytic degradability in subsoil (e.g. to evaluate their potential to leach into groundwater).

The characterization process prior to mitigation of industrial and military sites must consider a cardinal rule: that which is not sought is never found. Although the highest concentrations of contaminant generally will be focused at the source area, the characterization and clean up efforts also must identify and evaluate the extent and continued migration of contaminant plumes in soils, groundwater or surface water. This is critical because degradation often occurs in the areas of lower concentration associated with plume fringe, which may be far from the source.

A variety of technologies exist for the remediation of soil, surface water and groundwater at industrial facilities (e.g. thermal and chemical treatments, biological remediation technologies, soil washing and filtration; see Soesilo and Wilson, 1997; Nyer, 1998; Hyman and Dupont, 2001). Depending on the type of contamination and the threat to drinking-water aquifers, natural attenuation may also be an option (see also Chapter 24). When selecting a remedial technology, the decision will be influenced by potential effectiveness, reliability, implementability, cost and time constraints. Each technology has intrinsic advantages and disadvantages that can be optimized by carefully matching site-specific conditions with a remedial technology or suite of technologies. For example, many organic contaminants (e.g. petroleum hydrocarbons) are readily degraded by microbial communities under appropriate environmental conditions (see Chapter 4). Bioremediation seeks to optimize those conditions through a variety of in situ or constructed on-site mechanisms. Biological technologies such as these take advantage of and facilitate natural processes and, as such, are often favoured and are potentially less expensive, in comparison with more technologically complex approaches. The increased time frames associated with some biological remediation technologies may be more easily accommodated at sites controlled by government entities (e.g. military installations) than at those associated with commercial or industrial enterprises. Contaminants such as petroleum products or chlorinated solvents are amenable to such efforts.

Once a release to soils, waterbody sediments or other elements of a groundwater recharge area has occurred, there are many established and new methods to prevent or limit contaminant migration in soils and to control or reverse plume expansion in groundwater. These methods include physical controls (e.g. sheet piling, trenches/slurry walls/grouting, recovery wells, air sparging), physical separation (to reduce reactions) and chemical methods for contaminant control (e.g. oxidation/aeration, reduction, permeable reactive barrier, dual phase extraction), as well as in situ or ex situ degradation by physical or biological processes. Recent advances in phytoremediation, for example, have resulted in deployments of certain tree species known as phreatophytes (e.g. poplar, willow) to intercept contaminant groundwater plumes (Quinn *et al.*, 2001). Such biological control also may enhance degradation of some organic contaminants. Maintenance and operation costs of such a system are lower than for typical engineered systems (e.g. pump and treat) over the relative lives of the systems. Depending on local and regional hydraulic effects exerted by water bodies, surface water control may be an important element of a comprehensive strategy to prevent industrial impacts in recharge areas.

The most straightforward mechanism for addressing contaminated soil, generally above the saturated zone, involves excavation and off-site disposal. However, the quantity and character of soils, as well as the associated removal, transportation and disposal costs, may limit the utility of this option. In addition, the transport of contaminated materials to another location may not relieve the original landowner of legal liability.

23.2 MINING

As with industrial activities, control measures for mining activities involve prevention as well as remediation and monitoring whether process controls are being implemented. Due to the large scale of many mining activities and milling sites, retrospective mitigation of their environmental impact is often substantially more difficult than prevention. Further, groundwater protection strategies are needed for both the active mining period and the post-mining period, and have to include the mine itself as well as mine waste, milling facilities and atmospheric emissions. Control measures may be equally necessary for small mining sites, particularly where they are numerous and potentially lead to considerable contamination of groundwater (see Chapter 11).

As for industry, choice of site is the first and often most important measure to protect groundwater. Many countries require an environmental assessment study for new mining activities exceeding a certain size (number of employees, amount of ore excavated). Ideally, intersectional collaboration in this planning phase should involve public health authorities and water suppliers to help recognize the potential impact on groundwater resources. Numerical modelling of groundwater flow, hydraulic situation before, during, and after mining activities and the impact of mining on groundwater quality is a state of the art technique and often successfully performed. Groundwater modelling is also an important tool to determine appropriate locations for monitoring wells to be drilled in the region of interest for mining, in order to record groundwater flow and quality parameters. Moreover, an Environmental Impact Assessment (EIA, Chapter 20) should be performed taking into account the vulnerability of the groundwater, the type of ore mined and processed, and other environmental threats in the region. This will lead to a more sustainable mining activity by introducing appropriate treatment and processing techniques. The EIA should cover the entire time frame, i.e. the exploration of an ore body, the mining activity, the remediation measures taken and the post-mining land use.

23.2.1 Deep mines

Constructing and operating a deep mine usually requires groundwater withdrawal. A necessary control measure to prevent water pollution in some cases is water treatment if the water contains toxic elements above a critical level. Monitoring would address on a regular basis whether treatment is in place and properly operating.

A further measure for preventing contamination is limiting the use of hazardous chemicals in ore processing and, where use is inevitable, application and handling with special care. Control measures may involve limiting, budgeting and recording the amounts of such chemicals used. Areas where heaps and tailing ponds will be constructed have to be investigated carefully including geological and hydrogeological aspects; in many cases liners (e.g. geotextile; see also Chapter 24) are useful as additional protection against contaminant leakages.

Before closing a deep mine, potential contaminants (e.g. fuel, oil, machinery) should be removed. In numerous cases where this was not done, considerable amounts of contaminants and waste in the mine have led to groundwater contamination.

Refilling of tunnels and shafts with waste rock or fly ash is a common technique to avoid land subsidence. However, it may also help in establishing lower permeability in the flooded mine and act as reactive material. The chemical nature of such fill materials should also be considered. These materials may be a potential source of contaminants (e.g. metals) in addition to mined materials. On the other hand, they may also be selected to bind contaminants: calcite may buffer low pH values, while iron (Fe^0) acts as a reducing agent, and fly ash or brown coal seem to be effective in sorption. However, little is known about long term behaviour of reactive material in underground mines. Thus the choice of adequate refilling materials is an important groundwater protection measure but long-term surveillance will often be necessary to ensure that contaminants are not released in concentrations above critical levels. Controls to ensure that adequate measures are taken for closure may include the requirement of approval of plans for such measures by government authorities or a catchment protection body.

During controlled flooding of a mine, contaminated groundwater is pumped and treated until the contamination level has decreased to acceptable concentrations. In many cases, this may require an extended period of time, and alternative passive treatment techniques might be preferable. In some cases, hydraulic isolation of the mine area might solve the problem, but this can be expensive as well. Tracer experiments are common tools to investigate the hydraulic flow pattern in a deep mine. Constructed wetlands can be used as effective and inexpensive measures to treat surface water after the first flush has reached an acceptable value of contaminants (Younger, 2000). As long as the contaminated groundwater flows at shallow depths, reactive walls (i.e. subsurface permeable barriers built with reactive materials to degrade or immobilize water-borne contaminants) may be considered as a low cost measure (Blowes *et al*., 2000). Reactive walls or permeable reactive barriers are passive treatment systems: a ditch is excavated in an aquifer downstream of the contaminant source and refilled with permeable and reactive material (e.g. mixture of sand with iron). Since iron in its elemental form is a very strongly reducing agent, metal ions (e.g. uranium, chromium) will be transferred in their reduced redox state and in consequence precipitate. Thus groundwater leaving the permeable reactive barriers is purified by certain metals and organic contaminants efficiently and at low costs. All approaches to treating water from mines will require adequate surveillance of treatment efficacy which would be defined in a management plan.

23.2.2 Open pit mines

Since open pit mining usually destroys aquifer structure, this type of mining often has the most severe impact on groundwater on a regional scale. Legislation and governmental controls on surface mining in relation to groundwater use have been implemented successfully. To control sulphides, waste rock should be covered as soon as possible (see below). Carbonate as alkalinity buffer may be added as additional measure to compensate the pH value due to pyrite oxidation. Calcium phosphate also has been used to control acid generation (Evangelou, 1995).

The design of open pit mining activities must also account for the final shape of a mine lake. Rapid recovery of groundwater to the final level in such a lake is often targeted to minimize erosion and stability problems with the embankment. As discussed in Chapter 11, acid mine drainage may flow from the oxidized zones of aquifers and heaps towards the pit lake resulting in extremely low pH-values in the lake water. If surface water is available to fill the lake, water quality will be no problem in the very beginning as this is usually well buffered. However, hydraulic equilibrium between groundwater and the lake will establish itself with time and water quality may decline when the groundwater in contact with rock is contaminated due to the solution of secondary minerals and/or waste deposits. Therefore management action to protect groundwater from post-mining lakes and vice versa requires both consideration of these processes already in the planning phase for the activity and surveillance for the post-mining phase until new hydrological equilibrium between ground- and surface water, as well as chemical equilibrium between solids and water, have been reached. Acid mine lakes can be treated by means of liming with dolomite quicklime. The pH will rise to about six and high sulphate concentrations will decrease by the formation of gypsum. Time intervals of monitoring should relate to rates of change and may decrease as processes slow down.

23.2.3 Acid mine leachate

As pointed out in Chapter 11, acid mine leachate is one of the most severe potential groundwater impacts from this human activity. Approaches to controlling this involve keeping the oxygen supply to sulphide minerals as low as possible to avoid reactions producing sulphuric acid. This requires careful investigation of the distribution of sulphides in the mine area and its vicinity. Also, minimizing the dewatering cone of depression will reduce leachate. Refilling shafts and adits with material of fine grain size reduces the permeability in these artificial cavities and helps establish more natural groundwater levels during the post-mine period. This material also may act as reactive material, lowering the outflow of contaminants from the mine site (see Section 23.2.1). Where these measures are chosen – alone or in combination – monitoring their proper operation is needed on a regular basis to ensure their implementation. Depending on the setting, monitoring could include regular checks on pH and sulphate concentrations in order to control whether sulphide oxidation is still ongoing**;** on the depression cone; and on the amounts as well as type of refilling material actually used.

23.2.4 Heaps, piles, mills and tailings

Major sources of pollution from mining often are heaps, piles and tailing ponds. Waste rock and residues from ore milling and ore processing (‘tailings’) at new or operational mining facilities need to be handled with the same care as municipal or industrial wastes. Control measures to mitigate their impact therefore include many state-of-the-art techniques used for waste deposits, such as drainage and treatment of drainage water to meet the targeted water quality criteria, or placement of spoil heaps and tailings over areas of impermeable sediments such as clay or bedrock that will not allow leachate to reach groundwater. Alternatively a clay lining or a geo-textile fabric can be used to line the site intended for disposal of spoil and tailings, or a foundation pad can be constructed which is impermeable or has reduced permeability. In both cases care must be taken to contain or treat leachate that runs off from the site. Corresponding control measures address the function of such containments and whether they are intact. Control measures for sustainable mining may also include the addition of buffering minerals to heaps, e.g. a certain amount of lime stone or fly ash according to the amount of sulphide in the waste rock. This buffers the formation of acid mine drainage in situ.

Control measures for such approaches involve periodic assessment of whether seals are tight, and monitoring systems for groundwater quality up- and downstream will assist in verifying whether the approach taken is sufficient.

In many settings, earlier construction of heaps, piles and tailings without consideration of their impact on groundwater quality has led to problems now requiring remediation. For example, remediation of the uranium mining and milling sites which were in operation from 1946-1990 in the eastern part of Germany is costing the German Government about US$ 6.5 billion. Treatment of contaminated groundwater as well as surface water from deep mines during ongoing operation may be accomplished by means of classical treatment techniques, though this may be prolonged and costly. Thus alternative treatment techniques such as reactive walls, carbonate drains, and constructed wetlands are increasingly being used. Constructed wetlands have proved to be a promising tool for natural attenuation of mine-related contaminants (Hedin *et al*., 1994; Younger, 2001).

Physical shaping and capping of heaps and tailings is necessary to avoid erosion, dust transport and reduction of the amount of infiltration. If radioactive ores or waste rock with radioactive components occur on-site, this must be taken into account in designing covers or caps that can act as a radon barrier as well (Merkel *et al*., 2002). Tailings may be covered with wet or dry caps, the latter being most common. Again, control measures should ascertain that caps are in place and functioning.

Rehabilitation of old heaps and tailings requires a careful investigation of boundary conditions and impact on groundwater. This will show to what extent reshaping and capping of these heaps and tailings may be necessary to achieve slope stability, erosion protection and surface or groundwater protection. Passive water treatment techniques may be applicable for long-term protection of groundwater resources.

23.2.5 In situ leaching

Mining by in situ leaching (ISL) presents special concerns to groundwater quality since hazardous chemicals are used for the in situ extraction of ore by leaching (see Chapter 11). Approval of ISL mining by regulators should therefore require management plans which define control measures with operational monitoring systems as well as maintenance of all installations to ensure that groundwater clean up can be performed at the specific site. Monitoring is critical to ensure that no process chemicals leave the ISL mining site during operation. When ISL mining is terminated, the site should be cleaned until pre-mining or otherwise acceptable conditions have been established.

23.3 MONITORING AND VERIFICATION OF MEASURES CONTROLLING INDUSTRY, MINING AND MILITARY SITES

The control measures for industry, military sites and mining in drinking-water catchments proposed above range from planning tools in the context of broader environmental policy to specific technical measures such as structures, containments and operational controls. Selected examples are summarized in Table 23.1.

NOTE ▶ *The implementation of control measures such as those suggested in Table 23.1 is effectively supported if the stakeholders involved collaboratively develop management plans that define the control measures and how their performance is monitored, which corrective action should be taken both during normal operations and during incident conditions, responsibilities, lines of communication as well as documentation procedures.*

The implementation of control measures protecting drinking-water aquifers from industry, mining and military activities is substantially facilitated by an environmental policy framework (see Chapter 20).

Monitoring of the measures implemented is crucial to ensure that they are in place and effective. Table 23.1 therefore includes options for monitoring and verification of the control measure examples given. Most of these focus on checking whether the controls are functioning as intended, rather than on contaminant concentrations in groundwater. For planning, reviewing will address whether plans exist, are appropriate and are being implemented, particularly in the context of issuing permits for new or extended operations. Periodic auditing of plans is an effective tool for such surveillance. Likewise, reviewing of emergency response plans would assess whether they are appropriate and whether they are occasionally being used for appropriate facility training exercises.

Similarly, for control measures in design and construction, the first step is to assess whether or not they are adequate for achieving the protection target, and whether or not they are in place as indicated in the construction plan. For the day-to-day routine operation of controls, monitoring focuses on assessing whether they are functioning as they should, e.g. whether containments are sealed, mine drainage is being treated or waste management plans are being implemented.

Monitoring of controls for day-to-day operations is particularly important as these tend to slip if not taken seriously. Examples given in Table 23.1 include maintenance routines, specifications on amounts and types of chemicals to be used, safety rules for handling, transferring and storing hazardous chemicals and routines for pumping hazardous leachate from mines. Such rules will be specified in management plans and standard operating procedures. Their implementation can be monitored by checking records, e.g. of maintenance measures taken or amounts of chemicals used in process steps, as well as by occasional inspection of process steps, such as unloading tankers with hazardous chemicals or integrity of storage structures, and by interviewing technical staff on how these steps are normally performed.

NOTE ▶ *Options for monitoring suggested in Table 23.1 rarely include regular groundwater quality monitoring. Where control measures such as structures are poorly accessible, however, monitoring of selected indicator parameters in groundwater is suggested.*

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

Where spills and releases are suspected or where the risk that this may happen is elevated, monitoring to provide for early detection is important. Careful evaluation of both the hydrogeology and the facility operations will allow prediction of likely locations and flow patterns of initial releases. Monitoring for key parameters that would readily indicate a leak at these locations can provide early warnings. This may include groundwater sampling and analysis of selected indicator parameters that would readily reflect leakage and potential contamination. Contaminant analyses will also be an important control measure after decommissioning of industrial and military sites and in particular after clean-up and remediation of contamination. Generally, resources expended in monitoring result in reduced remedial costs (and potential enforcement) in the event of a release. In the context of monitoring for overall verification of the catchment management concept, it is often effective to include contaminants anticipated or known to occur from industry, mining and military activities in the catchment, particularly at the sites of these activities, but also at groundwater intakes.

Table 23.1. Examples of control measures for industry, mining or military sites and options for their monitoring and verification

Process step	Examples of control measures for industry, mining and military sites	Options for their monitoring and verification
PLANNING	Require permits for the location, design and operation of industries, manufacturing enterprises, mining and military sites (e.g. EIA)	Review (application for) permit with respect to adequacy of siting, planning and design as well as public consultation
	Require plans for post-operational safety of site as part of the permit for such operations which are likely to need post-closure management (e.g. mining or military training sites)	Require long-term financial commitments and post-operational management plans (e.g. for lakes resulting from open pit mining) for issuing permit
	Require environmental or chemical management plans, including waste management plans when issuing a permit (including e.g. probations or limitations of specific processes or chemicals; treatment for mines using in-situ leaching)	Review existence and adequacy of management plans; audit if possible
	Require emergency response plans for enterprises which operate with hazardous substances	Review or audit emergency response plans
	If drinking-water protection zones are designated, enforce keeping hazardous enterprises out	Conduct periodic site inspections
DESIGN AND CONSTRUCTION	Install and maintain temporary and/or permanent containment structures (tanks, caps, vaults) for storage and handling of hazardous chemicals, explosives, mine heaps, tailings and ponds	Review adequacy of design and compliance with plans and regulations Inspect sites and enterprises for compliance with plans, and structural integrity and function
	Remove or remediate contaminated soil	Analyse residual soil and groundwater samples
	Refill mine tunnels and shafts; remove/stabilize potential contaminants; remove contaminants (e.g. fuel oil), machinery before refilling	Conduct follow-up site inspection and monitoring
	Rehabilitate old heaps and tailings; treat leachate	
OPERATION AND MAINTENANCE	Control/restrict amounts and types of chemicals used in production processes and mining operations	Review records/reports of chemical use, storage of wastes and maintenance of systems Analyse in situ leachate for chemical concentrations
	Control storage, handling and disposal of high risk chemicals and wastes	Inspect compliance to codes of practice, standard operating procedures and/or chemical management plans
	Maintain containment structures for storage and handling of hazardous chemicals and explosives	Check whether maintenance plans have been signed off; occasionally inspect maintenance Monitor downstream groundwater for parameter indicating leakage
	Minimize acid leachate from mines by controlling dewatering cone of depression	Monitor water levels, pH, or sulphide
	Treat contaminated groundwater from (active or closed) mining operations until contaminant concentrations reach acceptable levels	Monitor operational parameters for treatment system chosen (e.g. condition of artificial wetland and water flow) Analyse selected contaminants in treated water
	Conduct post-operational management of sites potentially leaking hazardous substances	Inspect monitoring and maintenance by operators and evaluation of reports required by permit Monitor downstream groundwater for parameter indicating contaminant migration

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24

Waste disposal and landfill: Control and protection

A. Allen and R. Taylor

Waste disposal by landfill has led to the pollution of groundwater resources under a wide range of conditions around the globe (e.g. Sangodoyin, 1993; Ahel *et al.*, 1998; Christensen *et al.*, 1998; Afzal *et al.*, 2000). In the USA, Lee and Jones (1991) assert that approximately 75 per cent of the estimated 75 000 sanitary landfills pollute adjacent groundwater with leachate. Leachate derived from waste deposits (landfills, refuse dumps) includes a wide range of contaminants, depending on the types of wastes deposited (see Chapter 12). There is consequently a strong need, supported by legislation in many regions, to protect groundwater from the effects of waste disposal. This chapter provides an overview of current approaches towards this aim and explains their scientific rationale.

24.1 WASTE CONTROL

Control of the type and amount of waste placed in landfills is a basic measure to protect groundwater. In many countries legislation regulates the type of wastes deposited at MSW landfills: waste that is considered hazardous due to its ignitability, corrosivity, reactivity, toxicity and carcinogenicity (Sharma and Lewis, 1994) is not accepted at

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MSW landfills, but is separated and removed for specialized disposal. Industrial wastes classified as hazardous include solvents and metal-rich materials. At the household level, hazardous wastes include refrigerators, paint, a range of cleaning products, batteries and such automotive products as lubricants (Tchobanoglous *et al.*, 1993).

NOTE ▶ *In developing a Water Safety Plan (Chapter 16), system assessment would review the efficacy of control measures and management plans for protecting groundwater in the drinking-water catchment from waste disposal and landfill. Chapter 12 provides the background information about the potential impact of wastes on groundwater and provides guidance on the information needed to analyse these hazards.*

This chapter introduces options for controlling risks from wastes. As the responsibility for waste disposal usually falls outside that of drinking-water suppliers, close collaboration of the stakeholders involved, including the authorities responsible for landfill, is important to implement, upgrade and monitor these control measures. This may be initiated by the drinking-water sector, e.g. in the context of developing a Water Safety Plan or of designating protection zones (see Chapter 17)..

Legislation to gradually divert most organic waste from landfills has been introduced by several countries. It is designed to reduce overall waste quantities disposed by landfill and thus also the quantity of leachate produced in landfills, since biodegradation of organic wastes is the dominant source of leachate production. Separate treatment of diverted organic waste by aerobic or anaerobic digestion will lead to the production of considerable quantities of compost. To protect the underlying groundwater, the control of run-off from larger (i.e. commercial outdoor non-reactor) compost piles is necessary.

Separation or sorting of waste for reuse or recycling (e.g. paper, bottles, cans) is another key measure in controlling and reducing waste going to landfill. Waste separation and sorting, which should preferably take place at source, provide an opportunity to reuse or recycle waste materials and to compost organics. This not only reduces the amount of refuse disposed by landfill but also leachate production. In many countries, semi-automated waste separation and sorting takes place after collection at centralized materials recovery facilities. Runoff from such facilities needs to be controlled to avoid groundwater contamination. However, recycling and reuse initiatives generally require government support as recycled items are commonly more expensive to produce than the items they replace. Government support of recycling can be financial through creation of markets or through government purchasing policy.

Open refuse dumps, where waste disposal is unsorted and unregulated, are characteristic of many countries of the developing world and represent an increased risk to groundwater quality. In such settings, waste separation and sorting for reuse and recycling is often conducted on an informal basis either at points of collection or at the dump itself. Although some of these operations are officially sanctioned, most are unofficial. They represent an important function as an informal recycling system contributing to reduction of waste to landfill. Direct exposure to waste materials may, however, present a health hazard.

A waste reduction strategy successfully used in a number of countries has been the imposition of a deposit fee refunded upon return of, for example, bottles, cans, tins, paper and other items. Taxes specifically on packaging materials have been implemented in Germany, for example, to reduce unnecessary waste volume. Household composting can be promoted for further waste reduction by subsidized sale of home composting bins.

Waste reduction strategies may also include landfill taxes. These provide an economic incentive and generate revenue. The downside to consider in planning policy is that they may also promote illegal (uncontrolled) disposal practices. For instance, imposition of a charge for acceptance of construction and demolition waste at one landfill in Ireland led to a rapid drop in the quantity of such waste delivered to the landfill.

Waste incineration can be an effective strategy to substantially reduce the amount of waste that is landfilled. Adequately engineered systems can effectively control air pollution and toxic residues, including those from flue gas cleaning systems, can be encapsulated for safe disposal. A major drawback of this strategy is its high costs, which tend to distract from investments into other options such as recycling.

Industrial wastes are often more hazardous than municipal solid waste (MSW). Unregulated disposal, often on site, was commonplace in the past and remains a problem in some regions. Major contamination of groundwater resources can be avoided through specifically designed and managed disposal of wastes from such industries as smelting, electroplating and tanning industries. A case study showing planning steps taken to remedy unregulated disposal of industrial wastes is described in Box 24.1.

Box 24.1. Planning priorities for the remediation of contaminated groundwater in the metallurgical centre of Ust-Kamenogorsk, Kazakhstan

Metallurgical plants produce fluid and solid waste that is hazardous due to high (toxic) metal concentrations. Disposal of this waste without pretreatment and in locations with limited capacity to attenuate these metal contaminants can lead to groundwater pollution. Ust-Kamenogorsk is a city in northeastern Kazakhstan with a population of 290 000 that was a centre for metallurgy and heavy industry in the former USSR. As a result of uncontrolled dumping of industrial wastes over more than 50 years, 300 000 tons of toxic arsenic mud, 6000 tons of PCB-contaminated mud and 19 million tons of slag, clinker and sludge from metallurgical processes containing mobile metal compounds were stored on permeable ground. Another eight million tons of fly ash from coal-fired heat and power plants, containing fluoride and boron have been deposited within the city area. The alluvial aquifer underlying the city is the sole water resource for the city water supply but was heavily polluted by arsenic, boron, fluoride, cadmium, copper, lead, manganese, selenium and zinc. High chloride, nitrate and sulphate contents are encountered in the contamination plumes. Contamination plumes in the groundwater clearly relate to dumps of metallurgical sludges and to seepage of process water from leaking pipe work and cracked factory floors (von Hoyer and Muff, 2001).

Comprehensive remediation of contaminated lands in Ust-Kamenogorsk is not currently feasible due not only to limited resources with which to execute the clean-up but also because of the magnitude of the problem that features a large number of pollution centres, complex nature of the contaminants and the large area of the polluted land. In the interim, an approach was necessary that seeks to improve the environment and the living conditions in the city but recognizes the need for continued industrial activity that provides jobs and tax revenue. The approach also had to be integrated into the legal framework and taxation system of the public sector, waste management and city planning, recognizing explicitly that groundwater pollution by hazardous waste is related to the production methods applied by the industry. Several social and economic sectors need to be involved in this task: the central government, the regional administration and the industrial sector. The following actions were recommended:

Political actions:

- Separation of responsibilities for hazardous waste. Government: hazardous waste inherited from the USSR era; industry: hazardous waste generated after independence
- Adaptation of an environmental fee system, with the aim to financially support the development of cleaner production technology from the fees collected from pollution
- Allocation of State Environmental Fund for the construction of environmentally safe disposal sites for hazardous waste

Technical measures (level of priority):

- Safe central drinking-water supply to all city areas from unpolluted wellfields; closure of polluted household wells (high)
- City development planning: protection of operative and potential city wellfields, concentration of industrial activities in existing industrial areas and relocation of residential areas to unpolluted areas (high)
- Capping of abandoned hazardous waste deposits with multibarrier cover in order to reduce leakage of contaminants, recultivation (high)
- Retrofitting of the zinc and lead plant in order to reduce leakage of process water (high)
- Optimization of the hydraulic containment for contaminated groundwater in the zinc and lead plant area (high)
- Solidification of PCB mud, deposition and capping with multibarrier cover, recultivation (high)
- Modernization of water quality laboratory in the East Kazakhstan Ecology Administration (high)
- Establishment of a surface and groundwater data bank and development of a groundwater flow and contaminant transport model in order to monitor the impact of remediation measures and industrial activities and to protect the city water supply (high)
- Capping of closed fly ash dumps with multibarrier cover, recultivation (low)
- Upgrading of existing groundwater monitoring network (low)

Legislation on handling, containment and disposal of hazardous wastes is in place in many countries and chiefly addresses industrial and medical waste. Pretreatment (physical, chemical, thermal or biological) of some of these is an option to reduce their hazardous impact. Separate approaches may be needed for different types of hazardous wastes, depending on the health hazards they impose, and their source. Box 24.2 uses the example of wastes from health care facilities to highlight management approaches for such specific waste sources.

Box 24.2. Managing wastes from health-care facilities

Many wastes from health-care facilities (e.g. hospitals) require pretreatment before these waste streams can be unified with other similar waste and disposed of as household waste. For example, microbiologically contaminated waste should be disinfected or sterilized before it is handled in any other way, and wastes containing cytotoxic compounds should be incinerated. Radioactive waste and associated waste waters require separate collection, as well as storage until their radioactivity have declined. For the disposal or discharge of wastes containing pharmaceutically active substances, diagnostic agents and active disinfecting substances into the environment risk, assessment is – for most compounds – similar to that for other chemicals (in particular pesticides and other biocides). Some substances require special management strategies, e.g. antibiotics and disinfectants due to their ability to foster resistance, and cytotoxic compounds of which some show mutagenic, carcinogenic and fetotoxic properties (Eitel *et al*., 2000).

One option to reduce the environmental impact of hospital wastes on a local scale is to implement an environmental management system, e.g. according to the ISO 14000 standard which defines targets for use of specific substances and their emission. This can be combined with the introduction of health and safety management procedures (Kümmerer *et al*., 2001). Often the process of improving the safety of medical staff can be addressed together with the reduction of environmental impacts including impacts on groundwater used as drinking-water resource.

Avoidance strategies have proven successful in health care facilities. For example, because of their low biodegradability, Freiburg University Hospital, Germany has largely eliminated products containing benzalkonium chloride or other quaternary ammonium compounds, and alcohols or aldehydes are used instead. This has considerably reduced quaternary ammonium compound concentrations in the hospital's effluent. Another important element of avoidance strategies is information for users about the potential impact of drugs, diagnostic agents and disinfectants on water quality, if they are not properly disposed of or returned to the pharmacy (e.g. safety data sheets, package inserts, specialist information for pharmacists/dispensing chemists).

For further information on safe waste management from health-care facilities see Prüss *et al*., 1999; WHO, 2000; WHO, 2004a; WHO, 2004b.

24.2 SITING AND PLANNING OF LANDFILLS

As discussed in Chapter 12.1, little attention was historically paid to the siting of landfills. Rock quarries and open gravel pits were often exploited as they avoided the effort and expense of excavation. Landfills, nevertheless, tend to be located close to urban areas where significant volumes of municipal and industrial wastes are produced. Whether the intention is to store waste in containment landfills or employ a strategy of NA (see Sections 24.3.1 and 24.3.2), it is safest to position landfills in areas removed from groundwater drinking-water supply sources and on sites where the underlying geology is able to attenuate to some degree the leachate that is generated from the stored wastes (see also aquifer vulnerability in Chapter 8). Clay- and organic-rich materials (overburden or mudstone bedrock) are suitable as they both retard groundwater flow and interact with reactive contaminants in leachate. Unfortunately, it is commonly difficult to choose such ideal locations strictly on the basis of hydrogeological considerations as socioeconomic considerations, including the 'not in my back yard' syndrome, tend to dominate the process of selection of landfill sites. Onibokun (1999) notes that landfills and dumps in Africa commonly occur in poorer areas, where residents are often less able to prevent landfill in their own backyard, are unlikely to benefit from waste collection services, and invariably depend upon local, often poorly protected sources of water.

In many countries, a tool for commissioning a site for landfill is Environmental Impact Assessment (EIA; see also Chapter 20). These include licensing applications, public hearings, appeals and sometimes court cases. The site selection process can be assisted by a GIS approach that is integrated with rigorous geotechnical site investigations (Allen *et al.*, 2001). Areas underlain by aquifers used for drinking-water supply and their catchments would normally be identified and rejected for waste disposal during an initial exclusion step, whilst areas with favourable geological conditions would gain high positive weightings in the ensuing assessment of the residual areas remaining after the initial assessment step. A second stage to narrow down potential sites, involving considerations such as cost/distance analyses and visual impact assessments, is then followed by the geotechnical investigation, which can also fulfil the requirements of the EIA. A major requirement of an EIA at any proposed landfill site will be a detailed hydrogeological investigation to assess aquifer vulnerability and potential impacts to groundwater. Determination of the attenuation capacities of the subsurface materials underlying the site, which should also be undertaken, can enable assessment of the capacity of the site to attenuate leachate migrating from the landfill.

In many countries, applications for licenses are also required for existing landfills and dumps. Where these are unsuitably located relative to drinking-water resources or to aquifer recharge areas, and where the underlying geology gives inadequate groundwater protection, a license may be revoked or refused and the landfill forced to close. Licenses, whether granted to existing landfills or to new landfills, usually come with stipulations in the form of requirements and restrictions. Stipulations for new landfills usually include design and operational requirements based on site conditions established in an EIA, whereas for existing landfills, upgrading of groundwater protection measures and operational procedures may be demanded. Stipulations for all landfills will also include types of waste acceptable for disposal and types of waste not permitted. Unacceptable waste may include hazardous wastes, for which specialized disposal or incineration may be required. Other requirements will generally also include monitoring procedures and frequency, and possibly also maintenance provisions at closure.

A policy of minimum travel time between landfills and groundwater-fed drinking-water sources has been adopted in a number of countries, often within the concept of drinking-water protection zones, as discussed in Chapter 17. According to this policy, waste disposal facilities are prohibited in areas within a certain (e.g. 50-day) travel time (by groundwater flow) of a groundwater-fed drinking-water source. A key drawback to the travel-time criterion is that it requires an indication of the mean groundwater flow velocity in order to estimate an appropriate separation distance. In practice, this is difficult to determine due to the pronounced heterogeneity and complexity of many groundwater systems. More refined approaches base landfill site selection decisions on a more detailed understanding of groundwater conditions, and the ability of the natural environment to contain or alternatively attenuate contaminants in waste leachate. Groundwater flow conditions can be assessed from local borehole records (i.e. hydraulic gradient, aquifer thickness) and the results of pumping tests in the underlying aquifer (i.e. estimates of hydraulic conductivity). The geology of a potential landfill site and, hence, its natural capacity to restrict subsurface flow and attenuate contaminants, can be elucidated from drilling logs (if available) and geological maps of the area.

Further planning aspects critical to potential groundwater contamination are the size of a waste disposal facility and the rate at which refuse is deposited. These determine its operational lifetime. Also, planning and siting needs to include transfer stations and material recovery facilities to ensure that these are not polluting groundwater.

24.3 DESIGN STRATEGIES FOR LANDFILLS

Different approaches exist regarding strategies of protecting groundwater resources from the leachate generated by waste disposal. Two different design strategies for landfills are: *containment* and treatment of leachate on site versus *attenuation* through degradation, dilution and dispersion of leachate.

24.3.1 Containment strategy

Containment requires that all liquid and gaseous emissions produced within the landfill are contained and collected for treatment. The central aim of containment is, therefore, to minimize production of leachate by restricting access of rainwater to the waste, and to prevent its migration from the landfill of leachate produced. This is accomplished by enclosing the waste in artificial lining systems consisting of a landfill liner and cap. As a consequence, leachate drainage systems, containment ponds and leachate treatment facilities are essential additional components of modern containment landfills. Experience has shown that artificial membranes will eventually leak so modern designs usually include composite two-, three- and four-layer multibarrier clay/membrane liner systems (Figure 24.1). These multibarrier systems consist of sheets of artificial membrane, most commonly high-density polyethylene, interlayered with natural or bentonite-enriched clay layers (Seymour, 1992; Cossu, 1995). In the European Union, for example, landfill regulations make it mandatory to entomb waste using engineered lining systems except at sites with low in situ hydraulic conductivity (less than 10^{-9} m/s) (Allen, 2001).

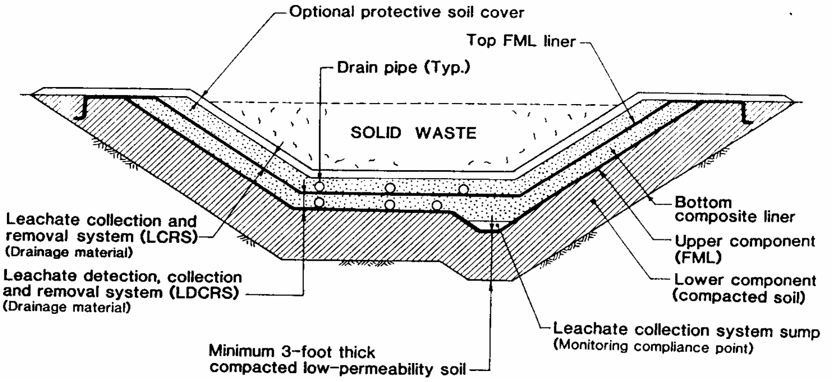

Figure 24.1. A sanitary landfill featuring an engineered lining and leachate collection system (Rowe *et al.*, 1997)

Leachate containment with engineered lining systems requires a suitable geological sub-base as a secondary barrier to groundwater when containment structures become permeable. Leakage can result from stress cracking of the membrane, cracking under cold conditions, damage, particularly from stones in the protection layer and from heavy dumping equipment, or failure of the membranes near welded seams (Rollin *et al.*, 1991; Surmann *et al.*, 1995). Synthetic liners are also susceptible to failure if installation is not subject to strict quality controls and favourable weather conditions (Averesch, 1995). Indeed, it is unlikely that any manufactured synthetic membrane is completely free of defects even prior to installation (Christensen *et al.,* 1994a). Lastly, some contaminants are able to diffuse through installed liners including intact geotextiles (Potter and Yong, 1993; Rowe, 1994).

Natural leachate containment is assumed under geological conditions where in situ hydraulic conductivity is less than 10^{-9} m/s. In practice, this is not always easy to ascertain. This is indicated by bulk hydraulic conductivities, derived from pumping or tracer tests over a larger volume, which are often several orders of magnitude greater due to preferential flow along discontinuities such as fissures (Gerber and Howard, 1996). Thus apparently low permeability strata such as glacial till and shale do not necessarily assure containment of leachate. When planning landfill based on natural leachate conainment, it is therefore important to validate the bulk hydraulic conductivity of the site.

An important aspect of containment is the aftercare timespan. Rates of waste degradation are a function of moisture content. Under wet conditions (i.e. uncapped landfills in climates where precipitation exceeds evaporation), an aftercare timespan of 30 years was initially assumed adequate to allow for degradation of waste to an inert state (Bookter and Ham, 1982). However, more recent work indicates that even under very wet conditions, complete degradation of waste may take at least 40-60 years (Wall and

Zeiss, 1995), and that some components (e.g. NH_4-N concentrations) may not have fallen to compliance thresholds of wastewater regulations for at least 100 years subsequent to landfill closure (Kruempelbeck and Ehlrig, 1999). On the other hand, for dry uncapped landfills in climate regimes where annual evaporative rate exceeds precipitation, giving rise to a moisture deficiency, degradation of waste may be considerably slower and estimates for dry landfills in water deficient areas suggest timescales in excess of 400 years (Röhrs *et al.*, 2000). The Gaza case study example given in Box 24.3 shows that depending on the composition of the wastes, leachate production may suffice for effective degradation.

Box 24.3. Groundwater protection in Gaza through upgrading of disposal standards

Collection and disposal of solid waste in the central part of the Gaza Strip are the responsibility of the Solid Waste Management Council – an autonomous public body governed by a board comprising the mayors of the eleven towns and villages that it serves. Services include collection and disposal of about 220 tons of MSW per day, generated by some 350 000 people. The sanitary landfill operated by this Council was designed and constructed in co-operation with the German Agency for Technical Cooperation.

At the onset of the project in 1994 a number of uncontrolled open dumpsites existed in the area under consideration. Adopting a strategy of containment, the first step in improving this situation was to assess soil and groundwater conditions at several locations. Based on this information and other factors, one of the existing dumpsites was chosen as a site for a central landfill.

In Gaza annual precipitation is between 200 mm and 450 mm; the wet season is October and April; no rainfall during rest of year; high annual evaporation between 1200 mm and 1400 mm. i.e. annual evaporative rate exceeds precipitation, representing moisture deficient conditions for most months of the year, so most experts were of the opinion that insignificant quantities of leachate would be produced.

Nevertheless, since groundwater is the main potable water source in the Gaza Strip, it was considered desirable to avoid any risk of further groundwater contamination. It was therefore decided to line the landfill site as detailed below: two asphalt liners with a bitumen mastic layer between the liners; coarse aggregates and drainage pipes to convey leachate to a storage pond; pumps and a sprinkling system for recirculation of leachate.

Decisions regarding capping, final cover and post-closure care were delayed until the quantity of leachate produced had been established. The lessons learned include:

Leachate quantities produced are high, contrary to expectation: Measurements indicate that the average leachate flow during the winter 1999/2000 to be 27.4 m^3 per day, and only slightly less during the dry summer season (25.4 m^3 per day), during which no leachate was expected at all. One possible explanation is that the composition of waste in Gaza differs from that for Western Europe. It contains more biodegradable organics with a high moisture content and more inert material, but less paper and other light fractions to absorb water. Because of its high initial moisture content this organic-rich waste biodegrades readily, promoted by the high temperatures prevailing in Gaza, producing large quantities of solubilized liquids even under moisture-deficient climate conditions, thus creating substantial quantities of leachate. Leachate samples, obtained and analysed, indicate that COD concentrations are in the range of 40 000 mg/l and BOD is about 11 000 mg/l, quite similar to values for young landfill sites in western Europe. These results indicate how incorrect conclusions can be arrived at if based on experience from quite different climatic and socioeconomic settings. Specifically, it proved to be important to have provided a lining in order to protect groundwater drinking-water resources.

The density of landfilled waste at the disposal site is exceptionally high: Based on before-and-after topographical surveys and calculations relating the volume filled to the total weight disposed of at the site, the density amounts to about 1.9 tonnes/m^3. Again this value met with disbelief from experts because this is almost twice the value at landfill sites in western Europe. Benefits of these high disposal densities are considerable:

- the life span of the site is almost doubled;
- capital costs for disposal on a per tonne basis are reduced by almost half.

This indicates that densities at disposal sites in the developing world may be considerably higher than in industrialized countries, again possibly due to the composition of the wastes, and the rapid biodegradation brought about by its high moisture content.

New approaches to final cover: The generation of leachate at the Gaza landfill site is likely to decrease substantially once the site reaches its capacity limit. The reason for this expectation is that the bulk of the leachate generated is due to the high moisture content of the waste, which promotes rapid degradation under the high temperature conditions prevailing at Gaza. When no more fresh waste is added, the moisture content will drop and degradation rates will decrease. Hence, once the site has been filled, the main source of leachate – fresh waste that has just been placed – no longer exists. This suggests that the application of an impermeable cap may not be required. It was therefore decided that the main consideration in the selection of cover material should be that it is a suitable substrate for plant growth. Organic and inert material from the landfill itself proved to be suitable for this purpose.

Appropriate solution for post-closure care: Considering that net evaporation is about 1000 mm per year, the surface area of the existing leachate storage pond is sufficient to allow evaporation of the quantity of leachate expected during the post closure period. It was therefore decided that, after closure of the site, the existing leachate storage pond be converted to an evaporation pond. This solution is inexpensive, reliable and almost maintenance-free.

Costs: As the (virtual) disposal density is about 1.9 tonnes/m3, capital costs are equivalent to about US$ 2.5 per tonne of MSW delivered to the site. The average household size in Gaza is 6.9 persons, disposal costs per household amount to about US$ 0.60 per month. This shows that relatively high standards of protection of groundwater resources can be achieved at moderate cost.

Isolating the waste from water (i.e. dry entombment) significantly reduces rates of degradation of the waste, thereby prolonging the activity of the waste and inhibiting, possibly by decades or centuries, its stabilization to an inert state (Allen, 2001). This extends the time span during which synthetic materials in artificial liners are subjected to the corrosive effects of leachate and the elevated temperatures generated by the exothermic processes operating with landfills. Recent research indicates that degradation of geomembranes occurs through oxidation processes over time (Hsuan and Koerner 1995; Koerner and Daniel, 1997).

Further considerations on the containment landfill strategy are its inherent costs and sustainability. The capital costs of installing an engineered lining and leachate collection system (Figure 24.1) will vary depending upon the size and lifespan of the landfill but are likely to prove prohibitive for many communities in low-income countries. Operational costs for one small landfill in Ireland, situated on a thick natural clay overburden deposit with a K value of $<10^{-9}$ m/s, and initially employing unlined cells, increased ten-fold when installation of a liner for future cells was required as part of its licensing stipulations. Leachate collection and treatment add significantly to the operating costs of containment landfills. There are, furthermore, the costs of other essential components of containment landfills including leak detection and landfill gas collection systems. Because of the large investment required for such technologies, landfills become economical on a large scale, promoting development of regional superdumps.

24.3.2 Attenuation strategy

The attenuation strategy allows leachate to migrate outwards from the landfill and takes advantage of the natural subsurface processes of biodegradation, filtration, sorption and ion exchange to attenuate the contaminants in leachate. The attenuation strategy is based on the dilute and disperse principle of leachate management proposed by Gray *et al.* (1974). A significant study at the time drew from a large body of field and laboratory investigations to highlight the efficacy of natural processes in attenuating leachate concentrations and indicated that, in appropriate situations, such an approach is effective in reducing the risk of pollution to water resources. This method of leachate management relied on natural low permeability and attenuation characteristics of geological barriers in the subsurface, primarily clay-rich overburden and, to a lesser extent, consolidated mudrocks, to prevent groundwater pollution by landfill leachate. The dilute and disperse principle of leachate control was superseded in the early 1980s by the containment strategy after having been discredited due to failures which occurred where the strategy was employed without adequate consideration of prevailing hydrogeological conditions.

The critical difference between the modern attenuation approach and the former dilute and disperse approach is that attenuation is an active management strategy, requiring the presence of a natural in situ or imported attenuation barrier to attenuate the leachate, whereas dilute and disperse relied on passive subsurface dilution and dispersion processes without the presence of a specific attenuation layer. Although the concepts are similar, it is now recognized that dispersion and dilution alone may not sufficiently attenuate leachate to adequately protect groundwater. More recent studies (e.g. Warith and Yong, 1991; Batchelder *et al.*, 1998; Yong *et al.*, 1999) support the conclusion that clay-rich overburden and mudrocks have the capacity to attenuate leachate. The effectiveness of the strategy is further confirmed by the fact that even within geological units of relatively high permeability and supposedly poor attenuation potential, such as sandstone, and sandy overburden, attenuation processes operate very effectively, and most pollutants are moderated within a few hundred metres (Christensen *et al*., 1994b; Williams, 1999; Ball and Novella, 2003; Butler *et al*., 2003).

Natural geological barriers, may be defined as low permeability clay-rich geological units (hydraulic conductivity <10^{-5} m/s), which can perform the function of an attenuating layer, enabling leachate to percolate slowly downwards, simultaneously undergoing attenuation by biodegradation, sorption, filtration and ion exchange processes with the clays in the unit (Allen, 2002). Extremely low permeability geological units (hydraulic conductivity <10^{-9} m/s) cannot fulfil an attenuation function as they perform in a similar manner to artificial or natural lining systems providing almost complete containment of all emissions. Similarly, geological units with higher permeability (hydraulic conductivity >10^{-5} m/s) do not provide sufficient confinement to leachate and are thus unsuitable for attenuation. The optimum permeability for attenuation is in the order of 10^{-6} to 10^{-8} m/s.

It is also recognized that the rate of degradation of waste materials can be enhanced by maximizing the flow of rainwater into the landfill leading to dilution of the leachate produced from the waste. Degradation of waste follows a well-documented path, with production of both leachate and biogas which vary in composition as degradation progresses. Waste with a high proportion of organics will produce significant quantities of leachate even under moisture-deficient conditions (see case study in Box 24.3), due to solubilization of organics by microbiological and biochemical processes. Rates of degradation are promoted by a steady flow of water through the waste, which also results in production of greater quantities of leachate but of a more dilute, less toxic nature.

The fundamental assumption of the attenuation strategy is that the underlying geology is able to moderate contaminant concentrations derived from landfill leachate to acceptable levels prior to groundwater discharge in a stream or water source (e.g. well or spring). However, not all geological units are able to fulfil this function, so a site selection protocol that includes an assessment of proximity to drinking-water wells, as described in Chapter 24.2, is an essential prerequisite to the adoption of an attenuation strategy. The attenuation mechanism may still be operated in unfavourable situations if natural clay or peat material is imported and installed as a liner to improve hydraulic conductivities and attenuation potential and if leachate migration is controlled. Nevertheless in certain types of terrain, such as karstified limestone, where groundwater flow occurs primarily along secondary fissures (i.e. non-intergranular flow) and attenuation of contaminants is limited, rapid and severe pollution of groundwater can result (Edworthy, 1989) and the attenuation strategy should be avoided.

Even in favourable geological situations, leachate migration should be controlled and monitored. Control measures include leachate collection and recirculation systems in order to prevent shock loading of the receiving environment. Location of monitoring wells needs to be based on detailed hydrogeological investigations or incipient groundwater pollution may be missed due, in part, to the limited predictability of groundwater flow from waste deposits (Chapter 12.2.3). Drainage, storage and recirculation of leachate prevent build up of leachate head as a guard against shock loading of the attenuation medium. The dilute nature of the leachate allows inexpensive treatment options by reedbeds or peat beds where leachate production is excessive.

A key attraction of an attenuation strategy is avoidance of the excessive costs of containment landfills that are untenable for many countries. It also avoids the long-term costs for maintenance and aftercare monitoring, which may be required for containment landfills for decades or even centuries after the site has ceased operating, as long as the waste remains active (Mather, 1995). Apart from a drainage system and containment ponds to control the leachate head in order to prevent shock loading of the attenuating medium and a monitoring programme, attenuation landfills have little attendant costs. The key constraint of the attenuation strategy, however, is the uncertain but genuine risk of groundwater pollution by leachate if attenuation proves less effective than assumed when selecting the site or if the site is not adequately managed (e.g. with respect to drainage measures).

24.3.3 Choice of strategy

Choice of strategy is likely to differ for upgrading existing landfills, remediating historic ones threatening a groundwater resource and for planning new ones. In choosing a suitable strategy for landfilling, with protection of groundwater for use as drinking-water a high priority, the following should be borne in mind:

- Every case is unique both with respect to natural hydrogeological conditions, land use and socioeconomic requirements, and the option chosen should be the most appropriate for the specific situation.
- The choice of site needs to be based on a detailed site selection process and needs to undergo a rigorous geotechnical investigation programme including hydrogeological surveys and delineation of the attenuation potential of the underlying geology (see also Chapters 8 and 14). Regardless of whether the chosen landfill management strategy is containment or attenuation, the underlying geology should have the potential to act as a groundwater protection barrier.
- The merits of containment with probable delays in stabilization of the waste to an inert state for many decades must be balanced against an attenuation strategy that seeks to degrade and stabilize waste in the shortest time possible.
- In balancing the economics of the containment strategy against that of attenuation landfills it is essential to include the costs of all ancillary elements required for each management option, and maintenance and monitoring costs after closure.

In many countries legislation now requires containment as well as collection and treatment of all leachate produced in the landfill. The rationale for this is protecting groundwater not only for drinking-water abstraction but also for environmental objectives, including the protection of soil and groundwater ecosystems in proximity to a landfill. The NA strategy, however, explicitly accepts environmental impact within some distance downstream of the landfill, in which no drinking-water abstraction would occur.

Economic constraints often limit the feasibility of technical options, particularly in developing countries. The preface of Botswana's Guidelines for the Disposal of Waste by Landfill highlights approaches towards incremental improvements (see Box 24.4).

Box 24.4 Extract from the Preface to the Guidelines for the Disposal of Waste by Landfill, Republic of Botswana, 1997

"The principal method of waste disposal in Botswana is by land burial. The uncontrolled burial of waste however can lead to serious groundwater pollution problems. For a country almost totally reliant on its already scarce groundwater resources, it is important that the standards of waste disposal by landfill are sufficiently improved to minimize the risk of pollution to water resources, and furthermore to public health and the degradation of natural resources. Water is a public commodity, and it is not ours to pollute as we wish. Due to the regional characteristics of water, any actions by users or polluters of a water source will affect other 'innocent' people downstream of that source. Legislation is being drafted which will require all landfill sites (as well as all waste facilities, transporters and even generators) to be licensed. In this respect it is essential that the licensing authority has guidelines on which to base their licensing decisions and the specific licensing conditions which they are to impose on each individual facility.

"The underlying philosophy and guiding principles used in drawing up the guidelines are that they should be:

- regionally compatible – to avoid the situation where Botswana could become a dumping ground for the southern African region, merely because it has lower environmental standards than neighbouring countries;
- specific to Botswana – to incorporate the specific social, cultural, economic and political criteria within Botswana;
- affordable without compromising on risk – to provide optimum protection of water resources.

"Because of its sparse population, the predominance of small villages in the country, and being a largely arid country, a degree of flexibility is needed in specifying requirements. A system of graded standards has therefore been introduced where the requirements could be adjusted up or down according to the risk imposed. Graded standards, an innovation developed and used extensively by the authors of the South African minimum requirements for landfills, are applied to different categories of landfill site (categorized according to its risk of pollution) as defined by the type and quantity of wastes to be landfilled.

"In this way the standards for landfilling of waste can be improved without incurring excessive development and operation costs, and without subjecting the community to an unacceptable risk.

"These guidelines are practical and specific to Botswana yet regionally compatible, and should be widely used by waste management practitioners. They should be seen as a dynamic set of requirements which will change with time to reflect the latest in relevant landfill technology as the results of world-wide landfill research dictates".

The challenge is to choose approaches that are viable in the longer term even if they do not immediately meet optimal technical standards. Graded standards for landfill are an innovation towards this aim. In South Africa, for example, minimum requirements for landfills vary according to different categories of landfill sites that are defined by the type and the quantity of wastes that are disposed by landfill. The Gaza case study (Box 24.3) demonstrates that locally adapted solutions may be very effective. It also shows that careful planning, taking into account the uncertainties when extrapolating experience gained in different types of settings, can lead to viable options at rather low costs.

Maintenance of an inventory of all waste disposal sites including those no longer in operation is critical since the risks posed by the landfill to the quality of local groundwater remain for decades. Where poorly sited, designed or constructed landfills or informal dumps are identified as hazard, an approach to remediation is to discontinue their use, cover them and, where necessary, monitor downstream groundwater quality.

Strategies for landfill sites (including historic sites and informal dumps) that are polluting or threatening aquifers used as drinking-water source include engineered barriers to leachate migration such as cut-off walls or trenches. A further option is to install defence wells to abstract leachate with high pollutant concentrations before the leachate plume reaches the drinking-water well. In some cases, particularly where there is evidence that hazardous wastes are leaching towards a drinking-water abstraction point, digging away and relocating the waste to a more adequately designed and managed landfill may be necessary. However, due to their high costs, these measures may not be economically feasible in all situations and relocating drinking-water abstraction wells may also be an alternative option.

24.4 OPERATION AND MAINTENANCE OF LANDFILLS

Regardless of the choice of strategy, controlling the operation of landfills is important to prevent groundwater contamination. Depending on the type of landfill and the type of waste, specific operational requirements may be set out in the license and operational controls need to enforce these. It may be effective to define these requirements in a management plan jointly developed by the water supplier(s) together with the other stakeholders and the surveillance authorities involved.

A key operational control is to monitor, record and document the composition and amount of waste delivered to the landfill (e.g. through inspecting and weighing waste trucks entering the landfill) and to turn deliverers away if the waste does not meet specifications. Documentation should include the origin and composition of the waste, and potential hazard classification. Random sampling is important for enforcing compliance with license requirements, and its approximate frequency would be defined in the management plan. Furthermore, documentation of where specific types or batches of wastes within the landfill are deposited may help trace the origin of particularly problematic leachate plumes detected by monitoring and thus enable targeted remediation.

Operational activities include landfill development. In containment landfills with a cellular structure, preparation and lining of future cells will necessarily occur. Whilst an active cell is operational, capping of recently active cells that have received their quota of waste will also be conducted. It is helpful to specify the lining and capping requirements and all other engineering systems to be installed in the license issued for the landfill, and to further detail them in the management plan. Licenses will also specify the height to which waste can be accumulated as well as the final profile of the capped landfill. On the basis of projected tonnages of waste to be deposited, the date of decommissioning of the landfill can be estimated. Daily operation of landfills may include the application of cover at the end of each working day for hygienic reasons in order to reduce wind blow and accessibility for flies, birds and vermin.

Drainage of leachate is important to reduce the hydraulic head of leachate, as this promotes leakage through artificial liners and can also lead to increased leachate migration rates through a clay liner. Accumulated leachate needs to be drained to a lined leachate pond from where it may be either tankered to a leachate or wastewater treatment facility or recirculated through the landfill to promote degradation of the waste. Depending on the type of waste deposited and ensuing leachate composition, treatment approaches range from wastewater lagoons to highly sophisticated methods such as reverse osmosis.

Regular maintenance of technical installations, e.g. leachate drainage systems, caps and barriers, is important to ensure that such technical controls are functioning. Operational monitoring is critical both for technical systems and for the implementation of management plans (see examples in Table 24.1), and they should therefore include a description of the operational monitoring to be conducted for each control measure.

Periodic monitoring of groundwater quality using a system of wells located both upstream and downstream of a landfill site is normally a license requirement for highly regulated landfills. It is particularly important for landfills based on the attenuation strategy. Monitoring will focus on indicator and bulk parameters such as conductivity and organic carbon, but may also include the hazardous components such as adsorbable organic halogen compounds and metals. Exceeding of threshold values may trigger actions such as closing and capping cells in a landfill, improving containment of new cells or establishing defence wells as outlined above.

24.5 PUBLIC PARTICIPATION AND EDUCATION

Public involvement, based on the communication of the relationship between waste disposal, groundwater and health, is important in two ways: health concerns often drive opposition to establishing waste treatment facilities or landfills, and the lack of understanding of health and groundwater concerns, particularly for hazardous wastes, is often a cause for careless, informal waste dumping.

Public participation in the selection of sites for landfill and waste treatment facilities can help to overcome the not in my back yard syndrome. Comprehensive dissemination of information about the plans, including the type and amount of waste envisaged as well as the intended measures to protect drinking-water resources and the environment, is the basis for public participation. This best commences at the outset of the selection process when the public is informed as to local/regional landfill site requirements in the context of the overall waste management strategy for the region. Public meetings would then follow at various stages in the selection procedure, with details of the selection process explained, concerns allayed and questions answered. In some countries, public participation in the management of landfills is encouraged. Consultative committees composed of local community representatives and the landfill managers serve to improve public perception of landfills and promote trust between the local community and landfill operators. They may also allay suspicion and fears over health and environmental issues as well as act as a conduit for information and concerns to be passed among stakeholders.

A widespread public understanding of groundwater protection issues is the prerequisite for avoidance strategies that require waste separation at the household level. Examples for this are campaigns to promote proper disposal and recycling of hazardous wastes such as batteries, motor oil, paints and solvents, or returning unused pharmaceuticals to the pharmacy. The development of an awareness of the potential of hazardous substances to contaminate groundwater-fed drinking-water supply may be particularly important for communities with much small-scale enterprise where they rely on shallow groundwater (see also Chapter 23). Public participation based on an understanding of contamination pathways from wastes to wells may also be important in making relocation decisions, i.e. to either move a waste dump or nearby wells if the distance between them has proven unsafe.

In various countries public participation is promoted by media advertising and by education campaigns, particularly of children at the earliest levels of schooling. Education is the key to changing public attitudes towards waste issues.

24.6 MONITORING AND VERIFICATION OF MEASURES CONTROLLING WASTE DISPOSAL AND LANDFILL

The protection and control measures for waste disposal in drinking-water catchments proposed above range from planning tools in the context of broader environmental policy to specific technical measures such as containing a landfill, managing leachate or constructing defence wells and trenches where leachate is threatening an aquifer. Selected examples are summarized in Table 24.1. Among these, planning and choice of site are particularly critical for waste disposal. This includes fundamental decisions on the disposal strategy with implications for operational controls. In some settings, some of these control measures may be suitable for integration into the WSP of a drinking-water supply (Chapter 16) and become subject to operational monitoring in the context of such a plan.

Monitoring of the measures implemented is crucial to ensure that they are in place and effective. Table 24.1 therefore includes options for surveillance and monitoring of the protection and control measure examples given. Most of these focus on checking whether the controls are operating as intended rather than on contaminant concentrations in groundwater. For planning, surveillance will begin with reviewing permits, the applications for which should not only demonstrate how aquifer vulnerability has been taken into account, but also how the landfill will be designed. If the strategy is controlled attenuation, review of the information base for assessing and predicting leachate migration will be particularly important. Where containment is intended, review of the application will address the choice of liner technology and leachate management. As waste deposits have long-term implications for groundwater, the review of applications for permits will also consider future land use and development planning in relation to groundwater demands. As landfill is a highly emotive issue in many cultures, reviewing applications for permits may take this into account by addressing whether and how planning has been based on public consultation and participation.

NOTE ▶ *The implementation of control measures such as those suggested in Table 24.1 is effectively supported if the stakeholders involved in waste disposal collaboratively develop management plans that define the control measures and how their performance is monitored, which corrective action should be taken both during normal operations and during incident conditions, responsibilities, lines of communication as well as documentation procedures.*

The implementation of control measures protecting drinking-water aquifers from waste disposal and landfill is substantially facilitated by an environmental policy framework (see Chapter 20).

For protection and control measures addressing design and construction, the first step in surveillance is to assess whether or not they are adequate for achieving the protection target, and whether or not they are in place as indicated in the construction plan. For landfills based on attenuation, construction controls will be few but controlling design may be important (e.g. for ensuring that protective layers of overburden are maintained or introduced as planned). For contained landfills, monitoring the quality of the liner and particularly its installation will be important. Documentation of the design and structure of the landfill, as well as of the criteria upon which planning decisions were based, is particularly important as it provides a basis for future situation assessment.

For the day-to-day routine operation of landfills, monitoring focuses on whether the amounts and type of waste deposited are in compliance with the permit (see Table 24.1). Such monitoring can include random sampling of waste delivered by trucks and checking accompanying documents. Further important operational controls include but are not restricted to leachate drainage and recycling or treatment as well as operation of defence wells or trenches where these are needed.

NOTE ▶ *Options for monitoring suggested in Table 24.1 include monitoring downstream groundwater for selected indicators of leachate migration.*

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

In addition to surveillance and monitoring of the functioning of control measures, groundwater monitoring serves to verify the whole drinking-water catchment management concept comprehensively. For waste disposal, groundwater monitoring is also a measure to control whether natural attenuation is performing as anticipated, whether leachate migration is within the area expected, and whether containments are leaking. It typically focuses on indicator and bulk parameters and in some situations will address specific substances of concern.

Table 24.1. Examples of control measures for waste disposal and landfill and options for their monitoring and verification

Process step	Examples of control measures for waste disposal and landfill	Options for their monitoring and verification
PLANNING	Require permit for siting based on a hydrological assessment (i.e. aquifer vulnerability, attenuation potential) including type and amount of waste and disposal strategy	Review (application for) permit with respect to adequacy of siting, strategy chosen and design as well as public participation
	Ban inadequate disposal of hazardous wastes in drinking-water catchments	Inspect existence of illegal disposal sites Monitor waste composition on permitted dumps
	Require waste management plans in drinking-water catchments (e.g. separate collection and disposal of hazardous wastes at specifically contained and managed sites or incineration systems)	Review existence and adequacy of waste management plans
	If drinking-water protection zones are designated, enforce keeping waste disposal out	Conduct periodic site inspection
DESIGN AND CONSTRUCTION	Where necessary, construct landfill with a basic liner to prevent rapid leachate migration but which also allows for maximum circulation and dilution of leachate Construct drainage for leachate and facilities for either recycling or treating it Cover or cap landfills when closed Improve attenuation potential by addition of imported clay or peat Where leachate migration threatens or pollutes the aquifer, construct barriers such as trenches, cut-off walls or defence wells	Review adequacy of design and compliance with plans and regulations Inspect construction site, particularly installation of liners On-site inspection
OPERATION AND MAINTENANCE	Control and document types of wastes deposited	Inspect records of site and of trucks dumping waste Review substance budgets of producers/users of hazardous materials (including infectious material) Perform random sampling and analyses of waste composition
	Maintain closed landfills	Inspect function and integrity of structures
	Maintain barriers such as trenches, cut-off walls or defence wells where leachate migration threatens or pollutes the aquifer	Monitor downstream groundwater for indicator of landfill leaching
	Collect and recycle leachate in the landfill to improve decomposition	Monitor pump performance and downstream groundwater quality

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25

Traffic and transport: Control and protection

A. Golwer

The most frequently occurring groundwater contaminants from traffic and transport are de-icing agents, particularly salt, fuel, including fuel additives, and some persistent herbicides e.g. atrazine. The issues are, therefore, less related directly to health than to drinking-water acceptability, except in specific local circumstances where a spill due to an accident can lead to a substance draining into an area vulnerable to groundwater contamination.

A number of approaches and control measures can be used to minimize pollution of aquifers with hazardous substances originating from traffic and transport related activities. These include proper planning of new transport links and routes, protective structures and containments, control of construction works, technical improvement of vehicles, impact assessment of substances used in transportation systems (such as de-icing agents or fuel additives), improved management of maintenance activities, regulation of the transport of hazardous goods through drinking-water catchments, rapid response to accidents involving spills of hazardous substances and treatment of traffic surface run-off prior to discharge. Monitoring programmes are important for determining the success of such prevention measures.

The existence of strategies and policies for protecting the environment from traffic and transport-related emissions facilitates the development and implementation of

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specific control measures to protect a drinking-water catchment. While their development and implementation may be initiated by the water supply or the public authority responsible for its safety, establishing effective control measures to protect groundwater usually requires intersectoral collaboration. This includes changes in public awareness and transport policies as well as training of people employed in the traffic sector. Successful implementation of strategies for the protection of groundwater resources may require a combination of education, fiscal, regulatory and supply-orientated measures (see also Chapter 20). Economic incentives can also contribute towards improving traffic behaviour or reducing the use of environmentally harmful types of traffic.

As with other potentially polluting human activities, giving priority to the prevention of groundwater contamination avoids the need for subsequent measures to reduce or remediate groundwater pollution, which is usually much more difficult and expensive. Where necessary precautionary measures are not immediately economically feasible, incremental improvement towards long-term targets should be envisaged, particularly through taking aquifer vulnerability into account when planning new transport systems or expanding existing ones.

As discussed in Chapter 13, situation assessment will collect information on the existing traffic and transport related infrastructure together with data on its proximity to groundwater systems and designated groundwater protection zones in order to assess pollution potential of aquifers. While many protection zone concepts seek to avoid traffic systems in the inner protection zone (i.e. close to abstraction points), they may be tolerated in the outer area of protection zones, though under the prerequisite of locally appropriate, largely constructional measures of protection.

NOTE ▶ *In developing a Water Safety Plan (Chapter 16), system assessment would review the efficacy of control measures and management plans for protecting groundwater in the drinking-water catchment from traffic and transport. Chapter 13 provides the background information about the potential impact of traffic and transport and provides guidance on the information needed to analyse these hazards.*

This chapter introduces options for controlling risks from traffic and transport. As the responsibility for these activities usually falls outside that of drinking-water suppliers, close collaboration of the stakeholders involved, including the authorities responsible traffic and transport, is important to implement, upgrade and monitor these control measures. This may be initiated by the drinking-water sector, e.g. in the context of developing a Water Safety Plan or of designating protection zones (see Chapter 17).

25.1 PLANNING AND REGULATIONS

Planning is particularly important in vulnerable groundwater catchments in order to limit or restrict construction of traffic facilities or to provide robust defences against pollutants entering the groundwater systems. For existing traffic lines, this may result in upgrading protective structures as well as in operational changes such as directing transports of hazardous goods to other routes (e.g. outside of the drinking-water catchment or protection zone). In planning the construction of new or extended traffic routes and facilities, the appropriate traffic system and route should be evaluated with respect to groundwater protection requirements. In some cases the construction of new traffic routes might be dispensed with through the improved utilization of existing routes. Aquifer protection may be an important criterion for decisions on the allocation of investments to railway versus road transport.

Requiring permits for the construction of traffic infrastructure may be an effective planning tool to assess plans for their impact on drinking-water and thus for the protection of human health. In this context, an Environmental Impact Assessment (EIA; see Chapter 20) of the proposed facilities and any alternatives provide a valuable basis for decisions. These include an assessment of the vulnerability of the aquifer to substances potentially emitted from the traffic lines intended and transport-related accumulation of hazardous substances with the potential to contaminate groundwater. Designing traffic infrastructure to include adequate drainage and disposal of drainage as well as less polluting maintenance procedures is easiest and least costly if included already in the planning stage. Management plans which restrict traffic or investment into protective structures may be more easily enforced if the drinking-water catchment or its most vulnerable areas are designated protection zones (see Chapter 17).

Frequently, not only transport activities themselves, but also the temporary construction areas associated with transport infrastructure pose a significant (though short term) risk themselves (see Chapter 13) and thus should be included in such impact assessments. Where soil and rock are to be removed, care should be taken to ensure this will not remove valuable protective layers to aquifer systems, or that dams created through construction unexpectedly affect flow paths to the groundwater. Management plans for the construction activity may be effective to define sufficiently protective procedures, and surveillance, e.g. through inspection of construction sites, is often critical for their implementation.

Regulatory requirements such as EIAs facilitate the selection of alternative routes and construction methods. Guidelines can be supplied for different construction activities as well as for raising awareness for pollution prevention. In many countries, numerous technical regulations at both a regional and a national level already exist which govern the construction and drainage of traffic routes and also – at least partly – take account of groundwater protection. An example directly addressing groundwater protection are the Guidelines for road construction measures and for existing roads in drinking-water protection areas in Germany (FGSV, 2002). Regulatory approaches have induced behavioural changes in some countries, e.g. safe disposal of motor oil and restriction of car washing to contained sites at service stations.

A further important regulatory and planning approach is the development of accident response plans, particularly for transport of hazardous goods, but also for fuel spills caused by accidents, as rapid clean-up can prevent or substantially reduce groundwater contamination. To be effective, such response plans need to be tailored for the respective setting. Further, it is important to train the response with the parties that need to react quickly in the case of a spill or accident.

A number of international regulations target reducing the environmental impact of transport, and their improved coordination and harmonization facilitates implementation of many measures. For example, the construction and operation of airports is regulated internationally (ICAO, 2000).

25.2 RUNOFF CONTROL

Whether or not collection and treatment of run-off from roads and other surfaces potentially contaminated by transport and traffic is necessary, depends both on the amount of traffic and on aquifer vulnerability and use. In rural areas, scattered run-off from low density traffic routes can percolate over a wide area, and the impact on groundwater quality is frequently regarded as harmless or tolerable if, outside of water protection areas, percolation occurs through a vegetation-covered area with an unsaturated zone at least 1 m thick.

In contrast, roads in built-up areas, as well as aircraft manoeuvring areas and airport aprons, are frequently connected to a drainage system. From less polluted roads this may be directed into a separate storm sewer system, not connected to the foul sewer system, and discharged into a receiving water body. Treatment is often not necessary or may be limited to retention basins (Figure 25.1) which settle some of the particulate load. These are best constructed at least 2 m deep in order to allow evenly distributed through-flow to avoid resuspension through turbulence. Where necessary because of aquifer vulnerability, they need to be impermeable to the underground. Retention basins may also be equipped with a vertical barrier to skim off low-density liquids such as fuels that float as upper layer on the run-off which need to be removed immediately after the pollution event. Removal of solids settled to the bottom, inspection and maintenance should occur at regular intervals and after events such as storms, extended periods of drought or frost and after accidents leading to loading of fuel and oil to the basin. Management plans are useful to define these maintenance activities, including the time intervals and responsibilities for their performance.

For collected run-off from very busy roads (average daily traffic volume >15 000 vehicles) treatment may be a necessary control measure before percolation to groundwater or discharge into surface waters, through mechanical separation as shown in Figure 25.1, through further steps such as percolation through artificial wetlands, or even by retention in larger basins and eventual discharge to a sewage treatment plant. The scale of treatment required for road run-off is determined by the hazard posed. Indeed, as the pollutant load and water volume can vary considerably over time, designing treatment to cope with the variable loading and volumes may be both difficult and expensive.

In some areas, road drainage systems may be connected directly into a sewage system, and the run-off can then be treated together with domestic and industrial waste water. While this is desirable in principle, combined collection of road drainage with sewage also poses problems. Elements of traffic-specific substances – for example, heavy metals – may enrich the sewage sludge and thus compromise sludge reuse and even cause problems for its disposal. Furthermore, during heavy rainfall events, combined sewerage systems can deliver huge volumes of run-off over short periods. Where storage volume is insufficient, this may swamp the treatment process, overflow into recipient water-bodies without treatment, or even place raw sewerage on streets and other areas. Therefore, planning for construction or upgrading of systems directing run-off to sewage treatment plants must include these considerations when calculating the dimensions necessary, particularly for retention basins.

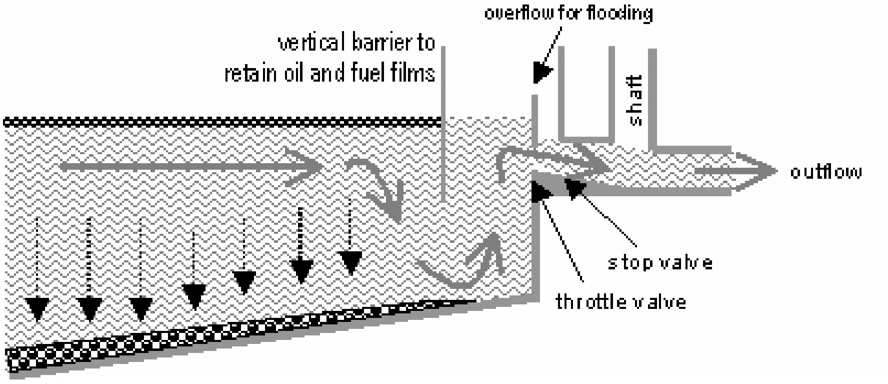

Figure 25.1. Basic scheme of a retention basin for particle sedimentation with vertical barrier to retain oil and fuel films

25.3 DESIGN AND MAINTENANCE OF PROTECTIVE STRUCTURES

The appropriate design for pollution prevention structures is best selected following a pollution risk assessment that considers both the type of traffic and the vulnerability of any aquifers in the vicinity. Legislation requiring protective structures in specified settings exists in many countries, often in combination with good practice codes or engineering guidelines (see e.g. DEFRA (2002) for the United Kingdom or FGSV (2002) for Germany). Typical pollution prevention designs incorporate the use of double-skinned tanks for fuel storage, bunding (i.e. containing) of above-ground storage facilities, adequate monitoring facilities in above and below-ground storage facilities (e.g. observation boreholes in tankpits, leak detection mechanisms in double-skinned tanks, pressure sensors in delivery infrastructure), overfill prevention systems, tanker stand areas with drainage capturing spills during delivery.

These engineered pollution prevention systems are effective only in combination with procedures for site operations, preferably described in a management plan and subjected to regular surveillance or audit. Regardless of the presence of pollution prevention structures, early detection of contaminant release is critical in protecting groundwater. This requires adequate training of operational staff to ensure that monitoring procedures are followed correctly, including regular (at least weekly) monitoring of volumes of stored fuels and other wetstock (at the most simple level, regularly conducting an audit of fuel delivered versus fuel supplied). It also requires developing staff awareness of, and interest in, the nature of plumbing and tank corrosion.

Where drainage and pollution preventing structures exist, it is essential that they be maintained in an optimum condition. For example, oil traps must be kept free of grit and other particles, otherwise they will overflow and fail in their protective capacity. Containments to prevent groundwater contamination (e.g. for fuel tanks) need to be inspected regularly to ensure integrity. Management plans would include regular maintenance programmes and operational monitoring to ensure such structures and treatment facilities are kept functional. Inspections of conditions downstream of outfalls are also recommended as part of a maintenance programme to ensure any adverse impacts are noted and dealt with on a timely basis. Improving the maintenance of roads, rail-track systems and airport operational areas forms part of effective control measures. The positive effects of road cleaning and major factors influencing cleaning efficiency were demonstrated by early investigation (Sartor and Boyd, 1972; Shaheen, 1975).

25.4 MINIMIZING USAGE OF HARMFUL CHEMICALS

Minimizing the amounts of chemicals used in maintenance of transport routes is an obvious method of reducing pollution potential. Management plans should be developed and applied to address applications of such chemicals. Subjecting the plans to regular audit helps ensure that they are implemented correctly. Restrictions on the use of particular chemicals in catchment areas will also aid in reducing pollution. For example, in the United Kingdom, following serious pollution of run-off from some stretches of railway lines with atrazine, the use of a different weed control method was adopted for designated sections of track in drinking-water catchment areas, resulting in a decrease in the levels of pesticide detected. The use of leaf and soil herbicides with quickly-degradable active substances, potentially within the framework of integrated vegetation control, represents an improvement in protective measures as compared with the current, largely preventative application of herbicides. A further example is the replacement of nitrogenous by non-nitrogenous de-icing agents on airfields.

Developments to reduce the health hazards from transport-related substances in groundwater include use of alternative chemicals less likely to pollute groundwater, environmentally more compatible fuels, mechanical (instead of chemical) snow, ice and weed clearance; these may all contribute to a coordinated pollution minimization policy. Groundwater pollution from air fields can be reduced by safer refuelling of aircrafts as well as switching fertilization of air-field lawns with highly soluble nitrogen compounds to controlled-release fertilizers, or by using more readily biodegradable pest control agents used against e.g. field voles (a burrowing rodent which needs to be controlled to reduce damage to air strips).

Regulating the nature, type and availability of maintenance materials can also aid in reducing pollution. Checklists of suitable alternatives can be provided to operators and local authorities to inform them of the benefits of their use over traditional substances known to cause pollution. Legislation banning the production, import or use of heavily polluting materials can be effective in avoiding the pollution they would otherwise cause.

25.5 ACCIDENTAL SPILLAGE AND DISPOSAL

A major pollution risk associated with traffic is spillage caused by accidents. Particularly in drinking-water catchments, the risk of accidents on roads can be lowered through technical measures (such as crash barriers, concrete skidding-walls, ramparts) and traffic-regulation measures (speed limits, overtaking bans, prohibition or restriction of vehicles with loads hazardous to water) (FGSV, 2002). National legislation banning the use and transport of specific hazardous substances or banning their transport on roads, particularly near vulnerable aquifers or in protection zones, can be an effective measure to prevent accidental pollution. Where this is not possible, issuing permits is an important control measure. They should take full account of the nature of the potential pollutant and detail emergency procedures. Where permits for the transport of hazardous goods are granted, emergency response plans to deal with accidents are important. These need to take into account that for some spills, the clean up chemicals used and subsequent washing of surfaces can introduce additional pollutants and aid in the spread of these.

Leaks from fuel storage tanks and pipelines are frequent sources of pollution. Such infrastructure should be subject to regular inspections and testing programmes. Even simple physical structures such as bunded fuel tanks (i.e. placing them inside a structure that can contain the tank's volume should it leak) can provide a significant reduction in pollution risk.

Groundwater pollution with hazardous substances from filling stations, fuel or waste transfer depots can be controlled by adequate design minimizing the risk of spillage and, if spillage should occur, accident response plans should be in place to allow rapid recovery of the spilt materials. If the facility is in the catchment of a public supply source, the responsible water authority should be informed and immediate remediation and control measures carried out, taking account of local conditions and the characteristics of the hazardous substance. These may include temporary closure of drinking-water abstraction to minimize drawing the pollutant into the aquifer, the construction of scavenger wells to remove the pollutant, or the diversion of the pollution through infiltration measures, thus producing a hydraulic barrier.

25.6 MONITORING AND VERIFICATION OF MEASURES CONTROLLING TRAFFIC AND TRANSPORT

The approaches to controlling traffic and transport in drinking-water catchments proposed above range from planning tools in the context of broader environmental traffic policy to specific technical measures such as structures, containments or the restriction of chemicals used in maintenance of traffic facilities. They also include process controls to check if transport facilities are operated properly in order to avoid contamination of drinking-water catchments. The most important measures are summarized in Table 25.1. In some settings, some of these measures may be suitable for integration into the WSP (see Chapter 16) of a drinking-water supply and become subject to operational monitoring in the context of such a plan.

NOTE ▶ *The implementation of control measures such as those suggested in Table 25.1 is effectively supported if the stakeholders involved collaboratively develop management plans that define the control measures and how their performance is monitored, which corrective action should be taken both during normal operations and during incident conditions, responsibilities, lines of communication as well as documentation procedures.*

The implementation of control measures protecting drinking-water aquifers from traffic and transport is substantially facilitated by an environmental policy framework (see Chapter 20).

In all settings, monitoring of the measures implemented is crucial to ensure that they are in place and effective. Table 25.1 includes options for surveillance and monitoring of the protection and control measure examples given. Most of these focus on checking whether the controls are operating as intended, rather than on contaminant concentrations in groundwater. For planning, surveillance will address whether plans exist, are appropriate and are being implemented, particularly in the context of issuing permits for traffic and transport infrastructure. Auditing of plans is an effective tool for such surveillance. Similarly, for measures addressing design and construction, the first verification step is to assess whether or not they are adequate for achieving the protection target, and whether or not they are in place as indicated in the construction plan. For the routine operation of controls, monitoring focuses on assessing whether they are functioning correctly, e.g. whether containments are leaking or whether restrictions on transport of hazardous goods through a catchment are being enforced (see Table 25.1).

NOTE ▶ *Options for monitoring suggested in Table 25.1 rarely include regular groundwater quality monitoring. Where containments and protective structures are poorly accessible for inspection of their integrity, however, monitoring of selected indicator parameters in groundwater may be needed to detect leakage.*

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

Some protection measures are difficult to monitor directly, e.g. integrity of a subterranean fuel road drainage pipes, and may most effectively be monitored by some parameter analysed in groundwater that would most sensitively indicate leakage (e.g. chloride, conductivity or in some settings, simply changes in water-table). Intensified monitoring of specific contaminants in groundwater may serve as a control measure after transport accidents involving hazardous goods or fuel spillage. Also, in drinking-water catchments with a potential for pollution by traffic and transport, overall verification of the catchment management concept would include monitoring of specific transport-related contaminants anticipated or known to occur.

Table 25.1. Examples of control measures for traffic and transport and options for their monitoring and verification

Process step	Examples of control measures for traffic and transport	Options for their monitoring and verification
PLANNING	Planning of new or expansion of existing traffic lines and facilities in relation to vulnerability of drinking-water catchments including e.g. siting, choice of materials and mode of construction, run-off collection, restriction of substances used in maintenance	Review plans with respect to the vulnerability and protection of drinking-water catchments
	Accident response plans in drinking-water catchments for releases of fuel and/or hazardous substances including lines of communication, immediate and subsequent measures	Approval, possibly audit, of accident response plans by public authority responsible
DESIGN AND CONSTRUCTION	Collect and adequately dispose wastes and wastewater during construction	Review adequacy of design and compliance with plans and regulations
	Install protective structures that minimize groundwater pollution through routine traffic and accidents, e.g. run-off collection, impermeable surface barriers, bunding of fuel tanks, crash barriers, retention and settling ponds, oil separators treatment facilities for run-off	Inspect sites regularly (including construction sites) and test functioning of facilities Assess integrity of containments, tanks, pipelines and tankers through visual inspection and leak monitoring systems
	Install specific protective structures of refuelling and vehicle maintenance stations (e.g. containment, drainage, oil separators)	
	Install terminal reception facilities for sewerage collection (e.g. from trains, busses, ships, planes)	
	Document construction details relevant for targeted response to spills, e.g. location of drainage pipes, sites for infiltration, location and construction of pipe joints	Check record drawings and documentation of construction details

Process step	Examples of control measures for traffic and transport	Options for their monitoring and verification
OPERATION AND MAINTENANCE	Maintain protective structures that minimize groundwater pollution from traffic, e.g. keep run-off drainage clear of obstacles, remove sludge from retention/settling ponds; repair sealed surfaces when damaged	Inspect integrity of structures and test functioning at regular intervals Where critical, monitor downstream groundwater for parameters indicating leakage
	Collect and adequately dispose wastewater from vehicles, terminal reception facilities, toilets; maintain sanitary facilities	Inspection of records for maintenance activities
	Maintain tanks and pipelines for fuel (e.g. kerosene, diesel, gasoline)	Regular inspection of integrity of containments (leak monitoring systems) Regular monitoring of fuel amounts delivered, stored and supplied; action plan to follow up discrepancies indicating losses
	Control amounts and types of chemicals used for maintenance of traffic lines (e.g. de-icing agents, herbicides)	Inspect records of chemical consumption, devices for use, storage of chemicals
	Devise and conduct regular staff training programmes in auditing and monitoring procedures such as to ensure early detection of leaks	Audit the number of staff trained and the frequency of that training Conduct regular checks of the efficacy of the training by testing staff response to a range of simulated scenarios Review staff performance during both simulated and real situations and modify the training if necessary
	Develop response plan for anomalies found during routine audits and monitoring	Conduct regular reviews of the plan with staff Evaluate staff response to real and simulated situations and revise the response plan if necessary
	Control traffic through protected drinking-water catchments to implement restrictions on the transport of hazardous goods as well as speed limits and bans on overtaking	Inspect records for traffic controls

25.7 REFERENCES

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