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Industry, mining and military sites: Control and protection

C. Teaf, B. Merkel, H.-M. Mulisch, M. Kuperberg and E. Wcislo

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.
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
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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 firefighting 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, functioning 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.

Action proposals:
- Technical structures to minimize foaming; venting on a buffer tank for the retention of the foam.
- Pipe installation above the retention room wall; constructing knock-down protection (big stones); regular pressure tests; street crossing over ground; double wall pipes installation.
- Creation of a reasonable canopy; moving the pipe in the bow area; renovation of the existing sealing area.
- 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 instal-
lations) 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\textsuperscript{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 contami-
nants) 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>
<thead>
<tr>
<th>Process step</th>
<th>Examples of control measures for industry, mining and military sites</th>
<th>Options for their monitoring and verification</th>
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</thead>
<tbody>
<tr>
<td><strong>Planning</strong></td>
<td>Require permits for the location, design and operation of industries, manufacturing enterprises, mining and military sites (e.g. EIA)</td>
<td>Review (application for) permit with respect to adequacy of siting, planning and design as well as public consultation</td>
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<td>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)</td>
<td>Require long-term financial commitments and post-operational management plans (e.g. for lakes resulting from open pit mining) for issuing permit</td>
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<td>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)</td>
<td>Review existence and adequacy of management plans; audit if possible</td>
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<td></td>
<td>Require emergency response plans for enterprises which operate with hazardous substances</td>
<td>Review or audit emergency response plans</td>
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<tr>
<td></td>
<td>If drinking-water protection zones are designated, enforce keeping hazardous enterprises out</td>
<td>Conduct periodic site inspections</td>
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<tr>
<td><strong>Design and construction</strong></td>
<td>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</td>
<td>Review adequacy of design and compliance with plans and regulations</td>
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<tr>
<td></td>
<td>Remove or remediate contaminated soil</td>
<td>Inspect sites and enterprises for compliance with plans, and structural integrity and function</td>
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<td>Refill mine tunnels and shafts; remove/stabilize potential contaminants; remove contaminants (e.g. fuel oil), machinery before refilling</td>
<td>Analyse residual soil and groundwater samples</td>
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<td>Rehabilitate old heaps and tailings; treat leachate</td>
<td>Conduct follow-up site inspection and monitoring</td>
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<tr>
<td><strong>Operation and maintenance</strong></td>
<td>Control/restrict amounts and types of chemicals used in production processes and mining operations</td>
<td>Review records/reports of chemical use, storage of wastes and maintenance of systems</td>
</tr>
<tr>
<td></td>
<td>Control storage, handling and disposal of high risk chemicals and wastes</td>
<td>Analyse in situ leachate for chemical concentrations</td>
</tr>
<tr>
<td></td>
<td>Maintain containment structures for storage and handling of hazardous chemicals and explosives</td>
<td>Inspect compliance to codes of practice, standard operating procedures and/or chemical management plans</td>
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<td></td>
<td>Minimize acid leachate from mines by controlling dewatering cone of depression</td>
<td>Check whether maintenance plans have been signed off; occasionally inspect maintenance</td>
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<td>Treat contaminated groundwater from (active or closed) mining operations until contaminant concentrations reach acceptable levels</td>
<td>Monitor downstream groundwater for parameter indicating leakage</td>
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<tr>
<td></td>
<td>Conduct post-operational management of sites potentially leaking hazardous substances</td>
<td>Monitor water levels, pH, or sulphide</td>
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<td>Monitor operational parameters for treatment system chosen (e.g. condition of artificial wetland and water flow)</td>
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<td>Analyse selected contaminants in treated water</td>
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<td>Inspect monitoring and maintenance by operators and evaluation of reports required by permit</td>
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<td></td>
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<td>Monitor downstream groundwater for parameter indicating contaminant migration</td>
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</table>
23.4 REFERENCES


