12 WATER QUALITY

Chapter contents

12 WATER QUALITY

12.1 Introduction

Industry uses water in various ways. Water in canals and rivers, for example, may be used for transport of goods. Industries have been located to make use of such transport networks and canals built especially to serve them. In recent decades there has been a move to consolidate steel making at large steelworks in coastal locations, and to make use of imported coal and iron ore. Water is also used in a wide variety of processes: as a medium for transport and separation of particles, for example in coal washing and gas cleaning, and for cooling. Industrial sites may contain lagoons where waste process water is trapped to allow the settlement of solids. Modern sites are likely to recycle much of their process water, but historically, discharges of process water may have resulted in severe pollution of adjacent watercourses with long-term contamination of sediments.

There is much European Community legislation relating to water. Legislation on water pollution of relevance to the reclamation of derelict land is described in Section 12.6.

12.2 Water and coal mining

12.2.1 Types of water discharges

Introduction

During coal mining there are three main types of water discharge:

- process water;
- mine drainage;
- surface run-off.

Process water

Water is used in coal preparation plants, in which the coal is separated from non-coal materials. The processes are similar to those described in Chapter 8 for the recovery of coal from spoil heaps. The material from the mine is immersed in water and the lighter coal particles are separated from the heavier shale particles under gravity. Some fine-grained particles of coal are carried over in the process water, and these are removed in a second separation stage which utilises froth flotation. In this process reagents which adhere preferentially to the coal particles are added to the water. The reagents used include oils and polyelectrolytes. The oils used frequently containing phenols. Air is then blown into the mixture and the chemical reagents cause air bubbles to be formed around the coal particles. These particles then float to the surface where they form a froth which can be skimmed off. The water is then removed by filtration to give a coal filter cake. The waste from the froth flotation process consists of water containing fine-grained particles (tailings). The water and tailings are separated by filter presses, or by placement in settlement lagoons, in which the tailings separate out under gravity. The supernatant liquid may then be discharged or returned as process water.[148]

At disused coal preparation facilities the condition of the settlement lagoons will depend on the extent to which they have become filled with tailings and on the water level. Such lagoons may remain as bodies of open water or as areas of unsaturated fine-grained silt.

Mine drainage

During mining operations, many mines require pumping to remove water from the workings. When mining ceases and pumping stops water levels rise and the mine floods. Flooding of the mine alters the hydrological conditions of the area and new discharges of mine water may appear.

Many shallow mine workings, less than 100m deep, are wet and the water level in them is affected by surface storm water which percolates into the mine through cracks, joints and faults in the strata.[181] Deeper mines are more likely to be isolated from surface water by impermeable strata and are likely to be relatively dry. However, sandstones associated with coal in the stratified coal measures of shales, sandstones and coal, are potentially water bearing rocks. Thus, if the sandstones outcrop at the surface they will tend to be recharged by rainwater, resulting in significant inputs of water into the mine.

Coal measures are sometimes overlain by younger rocks. These rocks may be important aquifers, such as the Triassic sandstones which overlie the coal measures over Eastern Britain. Shafts sunk through these aquifers have to be protected by pumping groundwater from the surrounding rock. On abandonment of the mine this pumping will cease and the shafts will act as conduits for movement of water into the mine.

Mines may also be connected underground so that pumping of water from one mine will influence water levels in an adjacent mine. An abandoned mine may not have reached a hydrologically stable condition if it is connected to working mines. Later closure of the working mines, with cessation of associated pumping, could alter the water level in the abandoned mine, causing new issues of water to appear. Changes in water level could also affect the air-flow patterns in the abandoned mine. Such changes have, for example, resulted in the onset of combustion in colliery spoil overlying an old mine entrance. Rising water levels in the mine pushed air out through the spoil and resulted in an underground fire which led to die back of vegetation planted as part of a reclamation scheme.[63]

Surface run-off

Pollution of surface run-off water may arise where spoil, tailings or stockpiled coal are exposed to rainwater. Pollution will be greatest where slopes are steep, and erosion maximised, and the distance to surface watercourses is short, with little opportunity for suspended solids to settle out.

12.2.2 Causes of poor water quality

Introduction

There are three principal types of water pollution associated with coal mining:

- suspended mineral particles;
- salinity (*i.e.* a high concentration of dissolved salts);
- acidity.

Other possible pollutants include mineral oil, exuded by mine strata into the mine water in some coal fields.[103]

In addition to pollution from mining activity, water pollution may result from wastes deposited in mine shafts. For example, at the Ravenscraig steel works in Scotland coke oven wastes and pickling acids were disposed of down disused coal mine shafts at the site. Groundwater contaminated with ammonia, phenols, cyanides and oil was found to be seeping into surface watercourses.[11]

Suspended mineral particles

Suspended mineral particles may be present in surface run-off from colliery spoil or tailings, where these are not protected from water erosion, for example by a cover of vegetation. The particles are generally inert, consisting of clay, quartz or coal.[103] High concentrations of dense suspended solids will blanket the beds of receiving watercourses, killing the benthic (*i.e.* bottom dwelling) organisms, which are a vital part of the aquatic food chain.

Salinity

The major salts in mine drainage waters are chlorides and sulphates. The salinity of mine waters is dependent upon the soluble ion content of the coal and surrounding rocks and tends to increase with depth. The more saline waters tend to contain significant concentrations of barium, strontium, ammonium and manganese as well as chloride and sulphate.[103] Some freshly exposed colliery spoils are also saline (see Section 5.3.2) and may cause saline surface run-off.

Acidity

Acid mine drainage is the principal cause of poor water quality arising from coal mines and is dealt with in detail in Section 12.2.3.

12.2.3 Acid mine drainage

Introduction

Acid mine drainage (AMD) results from the exposure of sulphide-containing minerals to water and oxygen. Sulphides are oxidised to sulphate and acid is produced. At the resulting low pH values many metal salts become more soluble, so the drainage water is therefore both acidic and metal-rich.

The predominant sulphide mineral associated with coal measures is pyrite. Pyrite is a widely distributed mineral, present in sediments formed under anaerobic conditions. Pure pyrite is iron (II) sulphide, FeS_2, although other metals may be present as impurities, including arsenic, aluminium, gold and, notably, manganese. AMD resulting from pure pyrite oxidation contains iron as Fe^{3+}, sulphate (SO_4^{2-}) and acidity, as H^+. The iron forms a precipitate of hydrated ferric oxide (ochre) which coats the beds of watercourses, rendering them unsuitable as habitats for benthic organisms. The high concentrations of other metals, notably aluminium, may also be toxic to aquatic life, particularly fish. AMD-affected waters are thus usually without fish and sometimes devoid of any aquatic life.

Pyrite may be present both in colliery spoil and *in situ* coal measures underground, AMD may therefore be produced both by the interaction of surface water with colliery spoil, and by the interaction of groundwater in the mine with pyrite-containing rocks. The latter produces polluted adit discharges and is the major source of AMD pollution.

There are four stages in the generation of AMD:

- oxidation of pyrite;
- mobilisation of the products of oxidation;
- neutralisation;
- secondary mobilisation.

Each stage is described in turn below.

The typical composition of AMD resulting from coal mining is shown in Table 12.1. The presence of aluminium and manganese ions in the AMD results from the secondary mobilisation of metal impurities present in the pyrite and in surrounding minerals.

Table 12.1: Typical composition of AMD from coal mining[259]

Constituent	Concentration (mg/l) except pH
SiO_2	90
Mg	80
Ca	200
Al	50
Fe	50-300
Mn	20-300
Sulphate	20-2000
pH	3.0-5.5

Oxidation of pyrite

The oxidation of pyrite has been discussed in Chapter 5, and the chemical reactions involved shown in Box 5.1. Oxidation of pyrite may be by atmospheric oxygen, which is a slow process, or by ferric (Fe^{3+}) ions, which is rapid. Ferric ions are produced by the oxidation of ferrous (Fe^{2+}) ions, released by the oxidation of pyrite. This reaction is slow except when it is catalysed by iron-oxidising bacteria such as *Thiobacillus ferrooxidans*. These bacteria are only active under acidic conditions (pH 2-4), so once the pH has dropped to these values pyrite oxidation is increased considerably and the pH falls rapidly.

Mobilisation

In the absence of water, the products of pyrite oxidation accumulate on the mineral surface and thereby inhibit further reaction. AMD is formed when these products dissolve and are transported away by the water. Alternate wetting and drying of pyritic spoil, or minerals in underground strata, enhances pyrite oxidation by washing away the oxidation products leaving a fresh reactive surface.

Neutralisation

Acid-consuming minerals, such as the carbonates ankerite and siderite, react with the acidity, increasing the pH and thereby reducing the solubility of metals. The metals are then precipitated as metal salts such as hydroxides, carbonates or hydrogen carbonates.

Table 12.2 gives examples of acid-consuming minerals and their neutralising capacities.

In any situation, both sulphide minerals and acid-consuming minerals are likely to be present. The relative amounts of the two types of minerals will determine whether long-term production of AMD will result.

Table 12.2: Summary of some acid-consuming minerals and their neutralising characteristics (from BCAMD Task Force, 1989[25])

Mineral	Composition	Acid-consuming potential †	Buffer pH
Calcite, Aragonite	$CaCO_3$	100	5.5-6.9
Siderite	$FeCO_3$	116	5.1-6.0
Ankerite	$CaFe(CO_3)_2$	108	-
Dolomite	$MgCa(CO_3)_2$	92	-
Gibbsite	$Al(OH)_3$	26	4.3-3.7
Limonite/Goethite	FeOOH	89	3.0-3.7

†The acid-consuming potential is given as the weight (grammes) of the mineral required to provide the same neutralising effect as 100g of calcite.

Secondary mobilisation

Due to its acid nature, AMD will cause weathering of other non-pyritic, non-acid-consuming minerals. This weathering can lead to the leaching of further metals into the AMD. In particular aluminium, which is toxic to fish at low pH, may be leached from clay minerals. In this way AMD can lead to the mobilisation of toxic materials from otherwise inert materials.

The extent and characteristics of this secondary mobilisation will depend on the type of minerals encountered by the AMD, in addition to chemical factors (pH of AMD, redox potential, adsorption phenomena, chemical composition of AMD), biological factors (presence of iron-oxidising and other bacteria) and, to a lesser extent, physical factors (particle size and shape, temperature, pressure of pore gases).

12.3 Water and steelmaking

Large volumes of water are used in the steel industry, mainly for the cooling of heat generating plant such as furnaces, in the processing of steel products, and in the cleaning of flue gases. The processes involved in steel making have been described in Section 9.1. Settlement lagoons for waste water may be present.

Water pollution may arise from the presence of water-mobile contaminants on the site. The wastes and contamination from iron and steel making have been described in Section 9.2, and those from coal carbonisation (used at integrated steelworks to produce coke) in Section 10.2.

Slags, the major waste, or by-product, of iron and steel production, generally do not give rise to water pollution. Occasional problems include the leaching of sulphur compounds from blast furnace slags and high alkalinity from steel slags.[83, 225] Flue dusts from iron and steel making furnaces, particularly electric arc furnaces, may contain metals in a water-soluble form.

The greatest water pollution is, however, likely to be found in areas where coal carbonisation was carried out, and in the associated by-products facilities. Polluting substances associated with these areas include volatile organic compounds such as benzene, toluene and xylenes, more complex organic compounds such as naphthalenes and polyaromatic hydrocarbons, and inorganic substances such as sulphates, cyanides and ammonium.

12.4 Assessment

12.4.1 Introduction

This section deals with assessment of disused coal and steel sites from the water pollution perspective. It is through the pollution of water that contaminated sites are most likely to have an impact outside of their boundaries. Water pollution is therefore an important issue which should receive close attention during site assessment and reclamation design. The principles of site assessment have been outlined in Chapter 2.

The first step in assessment of whether a site is, or has the potential to be, a source of water pollution, is to find out from archive studies and soil investigations whether there are substances on the site which are potentially polluting. Assessment could then proceed as follows:

- identification of water bodies which could be polluted by substances on the site *i.e.* potential targets;
- collection of information on these targets to assess the impact of any pollution;
- characterisation of existing water quality;
- determination of water pollution potential of contaminated materials.

12.4.2 Identification of target water bodies

Both ground and surface waters may be vulnerable to pollution.

Surface waters include streams, rivers and lakes within or adjacent to the site. Pollution may occur through erosion of particulate matter or seepages of dissolved or liquid contaminants into these waters.

Groundwaters vary from perched, near-surface, groundwater tables to deep regional aquifers.

The continuity between different groundwater units and between ground and surface water can be inferred from geological information obtained from published data and from borehole drilling. Pollution of groundwater units may lead to pollution of surface waters into which they feed. Such surface water may be remote from the site and, due to the slow movement of pollutants in groundwater, it may be some years before such pollution becomes apparent. Similarly, surface watercourses may flow across outcrops of aquifers downstream of a contaminated site. For example, parts of the chalk groundwater system of Kent, southern England, an important aquifer for water supply, have become polluted with chlorides from streams contaminated by coal mine drainage.[265] Ground investigations, in particular the drilling of boreholes (see Section 2.5.2), and the disturbance of contaminated materials associated with reclamation works, may connect previously separate groundwater units. If one of these units was uncontaminated prior to disturbance it may become contaminated by the other.

The ways in which ground and surface waters are interconnected is greatly influenced by mining activity. Mine passages may have intercepted flows of groundwater, with the result that groundwater emerges as adit discharges, rather than from the pre-mining springs. The effects of pumping of mines and flooding which follows the cessation of pumping after mine closure have been discussed in Section 12.2.1.

The direction and rate of groundwater movement are important factors to determine in order to assess groundwater pollution. Direction of flow is perpendicular to the groundwater contours, obtained by measurement of standing water levels in wells or boreholes. The rate of groundwater flow can be calculated from the hydraulic gradient and hydraulic conductivity (see Box 12.1).

Characteristics of surface and groundwaters may vary considerably under different weather conditions and at different times of year. Surface watercourses may only flow after high rainfall events, or there may be a steady flow throughout the year. Similarly groundwater bodies vary in

Box 12.1: Calculation of rate of groundwater flow[52]

Groundwater flow can be described using Darcy's Law:

$$V = -K\frac{dh}{dl}$$

where:

V = specific discharge *i.e.* the rate of flow through unit cross sectional area.

K = hydraulic conductivity, a measure of the permeability of the material.

$\frac{dh}{dl}$ = hydraulic gradient, difference between the groundwater level at any two points divided by the distance between them.

The unit cross sectional area to which V relates includes soils and voids. Groundwater flow is only through the voids so the actual velocity is the product of the specific discharge and the fraction of the unit cross sectional area occupied by voids *i.e.* the porosity of the material. If the porosity is 20%, the velocity of groundwater flow will be five times the specific discharge.

their response to rainfall. In some aquifers the amount of water within the matrix of the rock is small but there are many fissures through which groundwater flow is rapid. In such 'fissure-flow' aquifers there are large variations in groundwater level, with a rapid response to rainfall. The result of such variations in groundwater level can be that contaminated ground, which in the summer may be many metres above the groundwater table, may be inundated in the winter. By contrast, in aquifers in which flow is predominantly intergranular *i.e.* between particles within the matrix of the rock, storage capacity is far greater but flow slower. The response to rainfall events is therefore muted and the groundwater level does not show such large fluctuations. Mining activity is likely to increase the fissure-flow characteristics of an aquifer, increasing the variation in groundwater level.

12.4.3 Sensitivity of target water bodies

The impact of pollution from a particular source is influenced by the nature of the receiving water. In a heavily industrialised area, where extensive pollution of ground or surface water is already prevalent, water pollution from a contaminated site will have less impact on water quality than where the site in question is the major source of water pollution in the area. Evaluation of the potential benefits of preventing water pollution from the site requires information on the water quality upstream of the site and on inputs of pollution from other sources. The policy of the regulatory authority is also important. For example, there may be a long-term objective to improve water quality which will lead to a reduction in other pollution inputs. Such objectives are frequently the result of European Community legislation on water pollution (see Section 12.6). Reductions in inputs of pollution from other sources in the vicinity of a site will increase the relative importance of the pollution arising from that site, and thus the benefits to be gained by the prevention or treatment of that pollution.

Demands made on target water bodies will also influence the impact of water pollution. Surface water may support flora and fauna of ecological value. Some water habitats, particularly estuaries, can be important habitats for birds, despite historic pollution. Surface and groundwater is frequently abstracted for a variety of uses, and the contamination of water is most likely to be the subject of legal proceedings when pollution from a site causes water to be unsuitable for its intended use. The outcome of legal action is often to require the owners of the site causing pollution to remediate the pollution at their expense, *i.e.* the polluter pays.

12.4.4 Existing water quality

The effect of a site on ground and surface waters can be determined by collecting information on the existing quality of such waters. Any past water quality monitoring data should be consulted and sampling of surface and groundwaters carried out. Samples should be analysed for potential pollutants. Repeated sampling gives more reliable data than single samples as water quality can vary greatly at different times of year and under different weather conditions (see Section 12.4.2).

12.4.5 Water pollution potential of contaminated materials

Results of water monitoring may be inconclusive as to whether or not particular materials are sources of water pollution. An additional approach is to carry out leaching tests on the materials in question to determine the mobility of the potential pollutants they contain. Such tests involve placing a sample of the material in contact with a solvent, usually water, for a set period of time. The sample and water mixture may be shaken, or water may be allowed to percolate through the sample, simulating contact with rainwater. On completion of the contact period, the water is filtered and the filtrate analysed for the parameters of interest. Several standard leaching tests have been developed, for example DIN 38414-S4 in Germany.[74] Leaching tests provide a simple means of estimating the potential mobility of contaminants from a solid phase into a liquid phase.

Reclamation may reduce the particle size of a material or alter its environment. Leaching tests may be used to help predict the effects these changes will have on the leachability of substances from the material, and thus the likely water pollution impacts. They may also be necessary to allow decisions to be made on the disposal or reuse of materials which are to be excavated.

For pyritic wastes it may be necessary to evaluate the acid generation potential of the wastes (see Section 12.2.3). There are several methods by which this can be done.[25, 49, 144] The basis of the methods is to calculate the total possible acid production and then subtract the acid-consuming potential of the material to give a figure for net acid production (see also Box 14.7). The total possible acid production is that produced by oxidation of all the pyrite present in the material. Pyrite content may be either measured directly or inferred from the analysis of sulphur species. The measurement of total sulphur is the simplest procedure, though subtraction of sulphate sulphur gives a more accurate estimation of pyrite content, but one which still includes organic sulphur. Methods for the determination of pyrite in colliery spoils have been reviewed.[66] The method recommended by this review involves sequential oxidation with hydrochloric and then nitric acid followed by determination of the dissolved iron content. Further tests may be carried out on samples of materials found to have the potential for acid generation. These tests, known as kinetic tests, involve subjecting samples to weathering under laboratory-controlled or on-site conditions to determine the rates of acid generation.

12.5 Control of water pollution

12.5.1 Surface water

Surface water quality generally improves rapidly once pollution inputs cease. Therefore the strategy should always be to prevent inputs of pollution. Pollution arising from contaminated ground can be prevented by isolating the ground from water. Such isolation may be achieved by the installation of impermeable covering systems, cut-off drains to divert surface water before it reaches the contaminated material (see Section 13.6.3), and impermeable vertical barriers to prevent lateral movement of groundwater into or out of contaminated ground (see Section 11.3). Removal of contaminated materials from adjacent to watercourses may be necessary to facilitate this isolation from water. Treatment of contaminated ground to remove contaminants or to immobilise them (see Chapter 11) will also have the effect of reducing inputs to vulnerable surface watercourses, provided these treatments reduce the concentration of water-soluble contaminants.

Erosion of particulate matter directly into watercourses can be an important pollution input. Reclamation should minimise erosion through landform design and, where appropriate, the establishment of a vegetation cover.

Reclamation works constitute a particularly vulnerable period as there is inevitably some disturbance of materials on site which can lead to increased pollution of surface waters. In particular there may be 'wash-out' of suspended matter into watercourses at times of high rainfall. On vulnerable sites the input of surface run-off to working areas should be minimised by the installation of cut-off drainage prior to work commencing. Rainwater incident on the working areas should be drained to a treatment area and such treatment should, as a minimum, provide for the removal of suspended solids. Oil interceptors may also be required and further treatment by biological or chemical means may be necessary depending on the nature of the pollution and on the receiving water. It may be possible to discharge water to a sewage works or industrial water treatment works and so reduce the requirement for on-site treatment.

In some situations the pollution of surface water will arise even after reclamation. This is particularly so with acid mine drainage where pollution is generated by an ongoing natural process. In these situations long-term treatment of the water may be required to meet discharge standards set by regulatory authorities. The control and treatment of acid mine drainage is discussed in Section 12.5.3.

12.5.2 Groundwater

Treatment of polluted groundwater may be necessary for the following reasons:

- groundwater pollution is causing pollution of nearby surface waters;
- the groundwater is abstracted for some purpose which is affected by the pollution;
- to enable development of land;
- to prevent further dispersal of pollution;
- to improve and protect water resources which may be used at some time in the future.

Movement of groundwater is generally slow, with long migration times for pollutants. Therefore, unlike surface waters, reduction in pollution does not rapidly follow the cessation of pollution inputs. Clean-up of groundwater can be difficult and expensive, and is generally achieved by extraction of groundwater via pumping from wells, followed by treatment of the extracted water. Treated water may be re-injected into the ground or discharged to surface water.

Such pump and treat operations require extraction of a volume of groundwater several times greater than the volume of contaminated groundwater. This is because movement of contaminants is retarded, in comparison with movement of groundwater, by sorption onto soil particles. An understanding of the sorption and desorption characteristics of the contaminants in question is thus vital to enable prediction of the volume of groundwater requiring extraction. Further complications arise from the non-uniformity of contaminant distribution and the heterogeneity of the aquifer.[152] This will result in the dispersal of contaminants during groundwater extraction, increasing the effective retardation factor (the ratio of the velocity of groundwater to the apparent velocity of the contaminant). Insufficient consideration of this factor has lead to groundwater clean-up operations taking far longer than originally predicted.[142]

The volume of contaminated water extracted during groundwater pumping can be reduced by measures which minimise the extraction of groundwater from unpolluted strata, or which keep contaminated and uncontaminated groundwater separate. One such method is the dual pumping system developed in Denmark.[18] In this system groundwater is removed simultaneously from the contaminant plume and from underlying uncontaminated groundwater. Simultaneous extraction from pumps placed at the top and the bottom of a well which penetrates through the contaminant plume to uncontaminated groundwater, creates a water divide within the well, as shown in Figure 12.1. Water above the divide migrates towards the top pump and water below the divide towards the bottom pump. Variations in the rates of pumping can be used to adjust the position of the divide. In this way uncontaminated groundwater can be extracted separately and dilution of the contaminated groundwater avoided. If there is uncontaminated water above as well as below the contaminant plume, three pumps will be necessary.

Systems using two pumps in one well have also been used to remove free oil product from the surface of the water table. A deep pump removes groundwater to create a cone of depression at the well into which oil migrates from the surrounding ground, see Figure 12.2. This oil is then collected by a skimmer pump.[26] A disadvantage of this method is that oil migrating into the cone of depression may become immobilised by sorption onto soil particles. This is frequently referred to as 'smearing', and creates a reservoir of hydrocarbon contamination which can be a source of long-term groundwater pollution. A simpler system pumping oil and water from the surface of the groundwater only may be more effective. Extracted oil and water can then be separated or treated by a range of techniques.

A method which overcomes the problem of smearing is vacuum extraction; a vacuum is used to extract volatile contaminants from the unsaturated, vadose zone of the soil and to remove water from the saturated zone (dual vacuum extraction). Reduction in the groundwater level forms a cone of depression but volatilisation of hydrocarbons by the vacuum applied to the vadose zone reduces their adherence to the soil particles, giving more effective removal[154] This technique is discussed in Section 11.8.4.

Extracted groundwater is generally treated by the physio-chemical methods used for the treatment of industrial waste waters, though concentrations in groundwater are typically far less than in industrial effluents. Treatment systems used commonly include oil separators, carbon filters, coagulation/flocculation, chemical oxidation and aeration. Biological treatment systems are also used. Aeration systems, such as air stripping,[45] to remove volatile compounds, may require some treatment of exhaust gases to control air pollution. The major problem in design

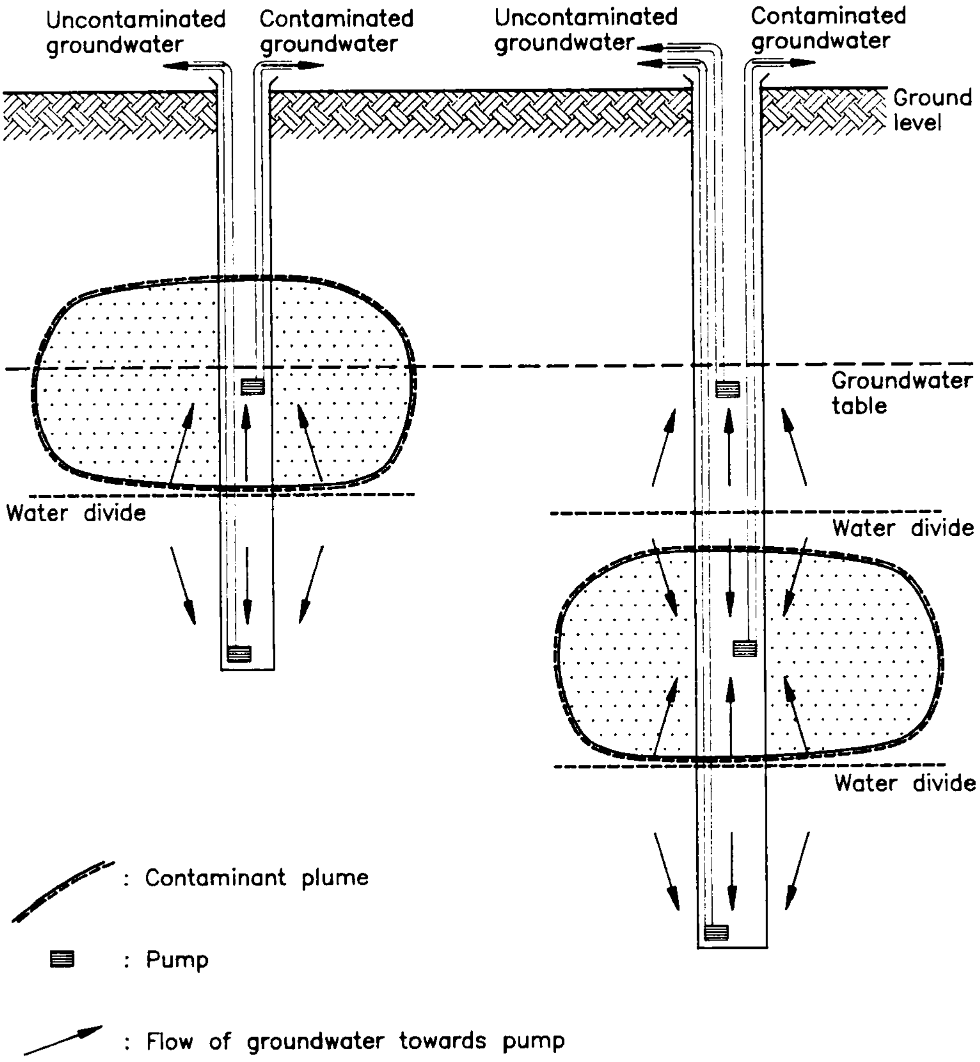

Figure 12.1: Dual pumping system

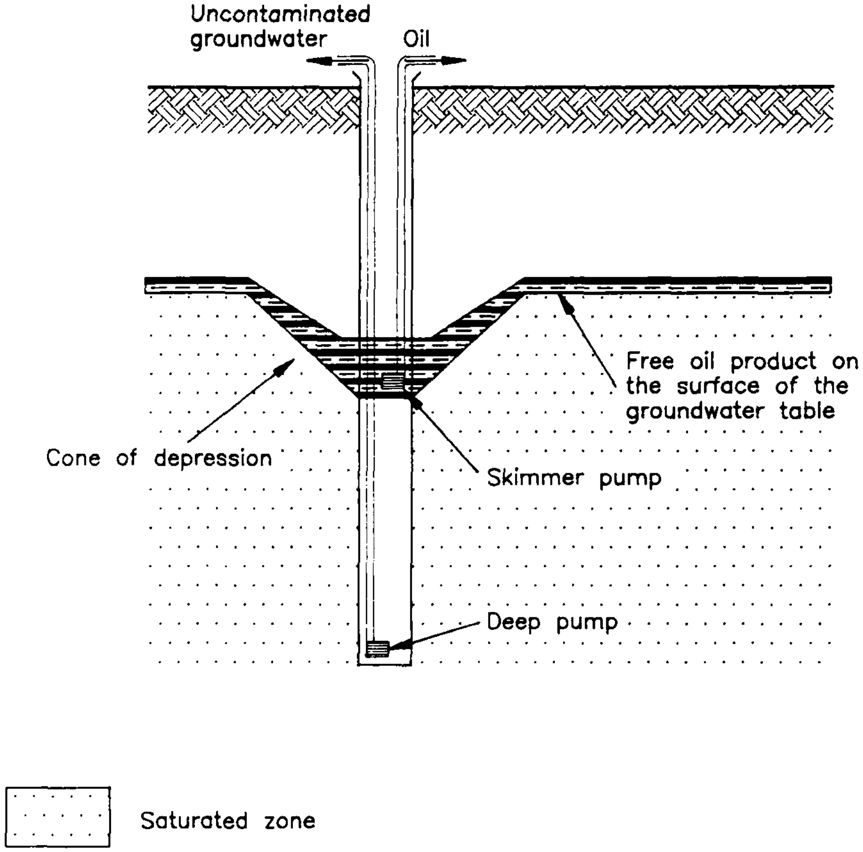

Figure 12.2: Removal of free oil product from the surface of a groundwater table

of treatment systems for extracted groundwater arises from the difficulties in predicting the quality and quantity of the water.[150]

12.5.3 Control and treatment of AMD

Introduction

There are a wide variety of potential control and treatment methods for AMD. Some of these methods are outlined in Table 12.3. Methods act by:

- preventing the oxidation of pyrite;
- preventing the formation of AMD;
- collecting and treating the AMD.

Prevention of pyritic oxidation

These methods act by:

- restricting the supply of oxygen;
- restricting the supply of water;
- inhibiting the iron-oxidising bacteria that catalyse the oxidation of pyrite.

Oxygen and water are both reactants in the oxidation of pyrite, so restricting their supply will reduce the rate of oxidation.

Phosphate-rich minerals, such as apatite, have been used in laboratory and small-scale field trials.[266] These minerals coat pyrite particles with insoluble iron phosphates and thereby isolate the pyrite from water and oxygen. Large doses of phosphates are generally required. In one study, however, acid production was reduced by 96% at a dose of less than 3 parts per thousand.[137]

Table 12.3: Acid mine drainage control measures

	Principle
Prevention of pyrite oxidation	
Bactericides	Inhibit the activity of *Thiobacillus ferrooxidans* and other iron-oxidising bacteria
Phosphates*	Coat pyrite particles with relatively insoluble iron phosphates thus isolating them from water and oxygen.
Soil or bog covers	Isolate waste from oxygen
Submergence of waste	Isolate waste from oxygen
Inundation of mines	Isolate waste from oxygen
Alkaline treatment	Raise pH resulting in metal precipitation and armouring of reactive surface of waste
Prevention of AMD formation	
'High and dry' waste placement	Isolate waste from ground and surface water and rainfall
Capping of waste	Prevent infiltration of rainfall
Stream/river sealing	Prevent infiltration of surface water into mines
Other civil engineering measures e.g. groundwater diversion, cut-off drainage	Prevent access of water to waste
Collection and treatment	
Alkaline addition	Raise pH resulting in metal precipitation
In-line system	Alkaline addition
Electrolysis *	Metal ions are separated from the water by the passage of an electric current through the AMD
Wetlands *	Cause metals to precipitate as oxides or sulphides and to be retained within the substrate material
Anoxic limestone drains	Raise pH and may cause metal precipitation

* Experimental or pilot-scale only

Submergence of spoil in water can be an effective means of reducing contact of the spoil with oxygen since the diffusion rate of oxygen in water is low.[25] Similarly, flooding of disused mines can significantly reduce pyrite oxidation within the mine. However, the cost of constructing impoundment structures to enable submergence of spoil is high and the potential environmental impact of placing mining waste in water bodies is great. Old wastes, which may contain large amounts of the products of pyrite oxidation, may liberate these products when first inundated, producing extremely acid water.

Sealing of mine entrances and allowing old workings to flood is common practice in many mining areas. When a disused coal mine in Pennsylvania was allowed to flood, acidity at the outfalls fell by some 75% and sulphate concentrations were halved, once the acidic mine water in the mine prior to flooding had been flushed out.[136] Use of this method should, however, be employed with caution and only after a detailed hydrological and geological survey to ensure that flooding the mine will not give rise to new issues of acidic water.

Covering of colliery spoil with organic matter, such as peat substitutes, then flooding to form a wetland, can reduce oxygen ingress to spoil since the covers themselves have a high oxygen demand.

Treatment of spoil with alkaline materials, such as lime, can be used to raise pH and thereby reduce pyrite oxidation through:

- precipitation of ferric ions (Fe^{3+}), which oxidise pyrite, removing them from solution;
- formation of an 'armour' of precipitated metals, principally ferric hydroxide, on the reactive surfaces of the pyrite preventing further reaction;
- inhibition of iron-oxidising bacteria, such as *Thiobacillus ferrooxidans*, thus preventing production of ferric (Fe^{3+}) ions from ferrous (Fe^{2+}) ions.

Large quantities of lime are generally required to treat pyritic spoils (see Section 14.4.5).

Organic materials, such as sewage sludge, are also reported to inhibit pyrite oxidation in colliery spoil, enabling a vegetation cover to become established.[162] Such organic materials may react by chelating ferrous and ferric ions, so they are unavailable for the reactions involved in producing acidity, and by providing buffering capacity against falls in pH.[195]

Bactericides can be used to inhibit *Thiobacillus ferrooxidans*, the bacterium primarily responsible for catalysing the oxidation of iron in pyritic ores. *Thiobacillus ferrooxidans* increase the reaction rate by up to 1,000,000 fold.[226] Anionic surfactants such as sodium lauryl sulphate (SLS), which disrupt the bacterial cell wall, have been much used, and food preservatives such as benzoic acid and sorbic acid have been investigated as their release into the environment may be more acceptable than that of surfactants.[195]

In full-scale trials, a single application of 0.25% SLS at about 5,000 litres per hectare on to mine waste was found to greatly reduce acidity and sulphate and iron concentrations in surface water for a period of 3-6 months.[181] Other laboratory and pilot-scale tests of SLS, sodium benzoate and potassium sorbate at concentrations of 15-40 ppm achieved reductions of iron and sulphate concentrations of above 70%.[218]

Slow-release forms of bactericide compounds are commercially available. Anticipated release lifetimes greater than 5 years are proposed for some products.[137] In the absence of these slow release forms, bactericides may need to be applied several times a year.[136] Although primarily applied to solid waste, commercial slow release bactericides are available for use in treatment ponds.[69] Removal figures of greater than 90% for iron, manganese and aluminium have been reported.

Prevention of AMD formation

Methods aiming to prevent formation of acidic drainage do so by isolating the pyrite-containing material from water. As water and the oxygen dissolved in it are necessary for the oxidation of pyrite, these methods will also inhibit pyrite oxidation. However, their main effect is to prevent the dissolution of the products of oxidation in flows of water, *i.e.* the formation of acidic drainage water, allowing instead the accumulation of the products of oxidation on the surface of pyritic materials.

An integrated program of control measures involves:

- diversion of surface water;
- interception of groundwater;
- prevention of rainwater infiltration;
- waste placement methods.

Surface water diversion can be achieved through the use of ditches or berms. These structures can be effective in the long-term, given sufficient maintenance. Surface water diversion measures, coupled with revegetation of the waste can reduce acid production by approximately 50%.[137]

'High and dry' placement of waste to isolate it from groundwater can be very successful in reducing AMD. For example, spoil can be placed on a porous pad with drains on the uphill side of the waste, to allow groundwater to bypass the waste.[161]

Capping of waste, to reduce or prevent rainwater infiltration, can be very effective, especially when combined with drainage methods to divert surface and groundwater (see Section 11.4). Cover systems use materials such as top soil, clays (including bentonite), tertiary-treated sewage sludge or compost. Synthetic materials are also used, including asphalts and tars, concretes, cements and plastic liners. Materials such as plastic films or liners act as impermeable barriers to water movement, but are easily damaged, can deteriorate and are expensive. Swelling clays, such as bentonite, are prone to cracking under dry conditions, allowing water to percolate into the underlying spoil through the cracks.[195]

All types of capping systems require long-term maintenance and the need for future replacement must be considered as part of a longer-term strategy.

Stream and river sealing can be used if hydrological investigation shows that infiltration of surface water from watercourses to an underground mine is a significant source of acid mine water. Watercourses can be redirected, culverted, piped or the stream bed sealed, and any deep faults can be grouted. An experimental grouting procedure has been used which involves injecting expanded polyurethane grout into the stream bed.[1] Disturbance to the stream bed is far less than would have been involved if the bed had been concreted. Flow losses into mine workings were successfully reduced in this way.

Collection and treatment of AMD

Principal methods of AMD treatment include:

- alkaline addition;
- constructed wetlands;
- anoxic limestone drains.

Alkaline addition involves the addition of chemicals such as sodium hydroxide, sodium carbonate, calcium hydroxide (lime), calcium carbonate or ammonia to AMD in a suitable impoundment. At the raised pH ferric ions precipitate out of solution as hydrated ferric oxide (ochre). Any ferrous ions dissolved in the AMD must be oxidised to ferric ions before this precipitation can occur, so oxidation, by mechanical aeration or injection of air or oxygen is often necessary.

Alkaline addition requires a long-term expenditure on chemicals and day-to-day supervision. Periodic collection of the precipitated metals is necessary and the resulting metal-rich sludge must be disposed of in an approved manner.

Alkaline addition has been used extensively at both active and disused mines but may often be a prohibitively expensive form of treatment. A pilot-scale 'in line system' (ILS) for treating mine drainage has been developed in the USA.[2] This system injects alkali (sodium hydroxide) into the flow of AMD, which is then passed through a jet pump and a static mixer. The jet pump entrains air and the static mixer provides effective oxidation of the AMD by forcing the air bubbles into solution. The degree of aeration achieved has been found to reduce alkali requirements.

A chemical treatment using barium sulphide to remove sulphate from AMD and so raise the pH has been developed in South Africa.[37] Electrolytic treatments are also being developed as an alternative to chemical neutralisation.[266] In the electrolysis cell hydrogen ions are reduced to form hydrogen gas at one electrode, thus raising pH, whilst iron and manganese are precipitated at the other electrode.

Constructed wetlands are increasingly being used to treat AMD from coal mines. There are over 400 such systems operating in the USA[136] and a few such systems operating in the UK. They have also proved effective in treating municipal sewage, metal mine drainage[202] and may be suitable to treat landfill leachate.[230]

In a constructed wetland, water passes through an area planted with wetland plants. These plants are typically emergent species such as reedmace (*Typha latifolia*) or common reed (*Phragmites australis*). The plants are rooted in a substrate which may be soil, gravel or organic-rich material such as spent mushroom compost, whilst their leaves and stalks are projected above the surface of the water which covers the substrate. Water flow may occur through the substrate, over the surface, or both.

Figure 12.3 shows some of the metal removal processes thought to occur in a wetland treating AMD. It is generally considered that the most important of these are metal oxidation/hydrolysis and sulphate-reduction. The first of these captures metals as oxides/hydroxides on and within the substrate, the second, as sulphides within the substrate.

Constructed wetlands offer several important advantages over other treatment systems, including:

- relatively low capital costs;
- little day-to-day supervision required;
- the provision of additional environmental and wildlife benefits.

However, substrate lifespan and disposal options have not yet been fully researched and design parameters are still under development. Also, a large area may be required to treat the flows of AMD commonly encountered.

A small wetland area for the treatment of AMD from a reclaimed colliery spoil heap has been constructed in Lothian Region, Scotland[62] and is shown in Photograph 12.1. The system consists of three lagoons, lined with clay, with top soil as the substrate and planted with *Phragmites australis*. Drainage water from the spoil is pretreated by anoxic limestone drains to raise the pH from 2.5 to 3.5. The wetland has been successful at reducing pollution of the adjacent watercourse.

Anoxic limestone drains (ALDs) are buried trenches of limestone. Under aerobic *i.e.* aerated, conditions the passage of AMD across limestone results in the 'armouring' of the reactive surfaces of the limestone. This armouring means that only a limited amount of the limestone can dissolve. Provided anoxic conditions within the ALD can be maintained, and AMD can be intercepted whilst still anoxic, the limestone of the drain can react with the AMD to generate alkalinity and raise pH without such armouring.[220]

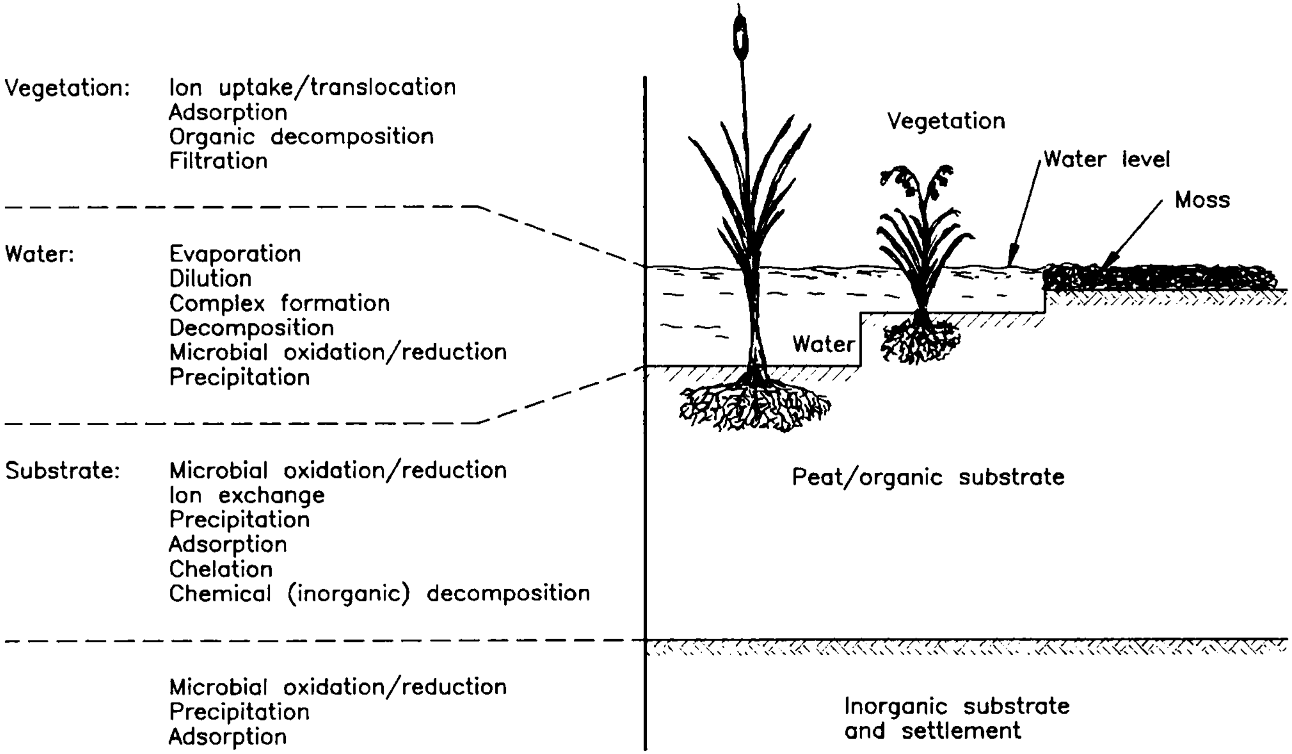

Figure 12.3: Metal removal processes in constructed wetlands (from Kleinmann, R.L.P. and Girts, M.A. (1987) Acid mine water treatment in wetlands: an overview of an emergent technology. In *Aquatic plants for water treatment and resource recovery* (Orlando, FL. 1986), edited by K.R. Reddy and W.H. Smith, 255-261, Orlando, FL.:Magnolia Publishing Inc.)

Photograph 12.1: The wetland treatment area at Gilmerton Bing, Lothian, UK. Water draining the colliery spoil enters the lagoon in the foreground from the anoxic limestone drains. *Phragmites australis* can be seen in the third lagoon of the system (source: Landscape Development).

Increased alkalinity favours metal oxidation, hydrolysis reactions and metal removal by precipitation, and therefore ALDs should discharge into a settling lagoon or constructed wetland in which the metal precipitates can be removed by settlement processes.

ALDs were originally developed as a pre-treatment for AMD entering constructed wetlands, but certain flows of AMD may lend themselves to treatment using only a combination of ALDs and settling lagoons.

12.6 Legislation and standards

12.6.1 Introduction

This section considers legislation on water at the European Community level. Such legislation is in the form of directives, which must be implemented in each Member State through its own laws and regulations. Directives concerning water pollution of relevance to land reclamation fall into two groups: directives concerned with pollution by particularly dangerous substances, and directives which lay down standards for water put to certain uses.[85, 89, 98]

12.6.2 Dangerous substances directives

These directives identify substances, or types of substances, which are particularly hazardous in the water environment and require Member States to control discharges of those substances with the objective of reducing or eliminating the pollution associated with them. Many of the substances covered will be found at steel and coal sites, so these directives have relevance to the control of pollution from these sites.

The primary directive concerning the discharge of "certain dangerous substances" is Council Directive 76/464/EEC of 4 May 1976 on pollution caused by certain dangerous substances discharged into the aquatic environment of the Community. This directive, commonly referred to as the 'dangerous substances directive', is a framework directive, which sets out general principles of control. Various daughter directives then set out emission limit values, quality objectives and reference methods for measurement and monitoring procedures for particular substances. 'Emission limit values' stipulate the maximum amounts of the substance which can be released from particular industrial processes, per unit of production. 'Quality objectives' define maximum concentrations within receiving waters. Quality objectives may be different for fresh and saline waters, but they do not vary according to the use of the water. The protection of groundwater is dealt with in the Groundwater Directive;

Council Directive 80/68/EEC of 17 December 1979 on the protection of groundwater against pollution caused by certain dangerous substances.

Both directives contain two lists of families and groups of substances in an Annex. The lists in the two directives are similar, but not identical (see Boxes 12.2 to 12.5). Directive 76/464/EEC requires Member States to take steps to eliminate pollution by List I substances and reduce pollution by List II substances. In the groundwater directive Member States are required to prevent introduction of List I substances into groundwater and limit introduction of List II substances so as to prevent pollution. In both directives the definition of pollution takes into account the harm caused by a substance, rather than simply the presence of a substance.

Box 12.2: Dangerous Substances Directive 76/464/EEC. List I

List I of families and groups of substances

List I contains certain individual substances which belong to the following families and groups of substances, selected mainly on the basis of their toxicity, persistence and bioaccumulation, with the exception of those which are biologically harmless or which are rapidly converted into substances which are biologically harmless

1. organohalogen compounds and substances which may form such compounds in the aquatic environment,
2. organophosphorus compounds,
3. organotin compounds,
4. substances which have been proven to possess carcinogenic properties in or via the aquatic environment,
5. mercury and its compounds,
6. cadmium and its compounds,
7. persistent mineral oils and hydrocarbons of petroleum origin, and for the purposes of implementing Articles 2, 8, 9, 14 of this Directive:
8. persistent synthetic substances which may float, remain in suspension or sink and which may interfere with any use of the waters.

Box 12.3: Dangerous Substances Directive 76/464/EEC. List II

List II of families and groups of substances. List II contains:

- substances belonging to the families and groups of substances in List I for which the limit values referred to in Article 6 of the Directive have not been determined,

- certain individual substances and categories of substances belonging to the families and groups of substances listed below, and which have a deleterious effect on the aquatic environment, which can, however, be confined to a given area and which depend on the characteristics and location of the water into which they are discharged.

Families and groups of substances referred to in the second indent

1. The following metalloids and metals and their compounds:
    1. zinc
    2. copper
    3. nickel
    4. chromium
    5. lead
    6. selenium
    7. arsenic
    8. antimony
    9. molybdenum
    10. titanium
    11. tin
    12. barium
    13. beryllium
    14. boron
    15. uranium
    16. vanadium
    17. cobalt
    18. thallium
    19. tellurium
    20. silver
2. Biocides and their derivatives not appearing in List 1.

3. Substances which have a deleterious effect on the taste and/or smell of the products for humans consumption derived from the aquatic environment, and compounds liable to give rise to such substances in water.

4. Toxic or persistent organic compounds of silicon, and substances which may give rise to such compounds in water, excluding those which are biologically harmless or are rapidly converted in water into harmless substances.

5. Inorganic compounds of phosphorus and elemental phosphorus.

6. Non-persistent mineral oils and hydrocarbons of petroleum origin.

7. Cyanides, fluorides.

8. Substances which have an adverse effect on the oxygen balance, particularly: ammonia, nitrites.

Box 12.4: Groundwater Directive 80/68/EEC. List I

List I contains the individual substances which belong to the families and groups of substances enumerated below, with the exception of those which are considered inappropriate to List I on the basis of a low risk of toxicity, persistence and bioaccumulation.

Such substances which with regard to toxicity, persistence and bioaccumulation are appropriate to List II are to be classed in List II.

1. Organohalogen compounds and substances which may form such compounds in the aquatic environment.
2. Organophosphorus compounds.
3. Organotin compounds.
4. Substances which possess carcinogenic, mutagenic, or teratogenic properties in or via the aquatic environment.
5. Mercury and its compounds.
6. Cadmium and its compounds.
7. Mineral oils and hydrocarbons
8. Cyanides.

An important difference in the approach taken by the two directives is the relationship between List I and List II. In the groundwater directive substances belonging to the groups in List I are to be treated as List I substances unless they pose a low risk of toxicity, persistence and bioaccumulation. In the dangerous substances directive substances are to be selected for List I status, from the families or groups of substances given in List I, on the basis of their toxicity, persistence and bioaccumulation. Substances do not have List I status unless emission limit values and quality objectives have been laid down by daughter

Box 12.5: Groundwater Directive 80/68/EEC. List II

List II contains the individual substances and the categories of substances belonging to the families and groups of substances listed below which could have a harmful effect on groundwater.

1. The following metalloids and metals and their compounds:

    1. Zinc
    2. Copper
    3. Nickel
    4. Chromium
    5. Lead
    6. Selenium
    7. Arsenic
    8. Antimony
    9. Molybdenum
    10. Titanium
    11. Tin
    12. Barium
    13. Beryllium
    14. Boron
    15. Uranium
    16. Vanadium
    17. Cobalt
    18. Thallium
    19. Tellurium
    20. Silver.

2. Biocides and their derivatives not appearing in List I.

3. Substances which have a deleterious effect on the taste and/or odour of groundwater, and compounds liable to cause the formation of such substances in such water and to render it unfit for human consumption.

4. Toxic or persistent organic compounds of silicon, and substances which may cause the formation of such compounds in water, excluding those which are biologically harmless or are rapidly converted in water into harmless substances.

5. Inorganic compounds of phosphorus and elemental phosphorus.

6. Fluorides.

7. Ammonia and nitrites.

directives. Until this happens substances belonging to the families and groups of substances given in List I of the Annex are to be treated as having List II status.

Daughter directives to 76/464/EEC are shown in Box 12.6 and the substances with List I status as a result of those directives in Box 12.7.

Box 12.6: Daughter Directives to 76/464/EEC

82/176/EEC	On limit values and quality objectives for mercury discharges by the chlor-alkali electrolysis industry.
83/513/EEC	On limit values and quality objectives for cadmium discharges.
84/156/EEC	On limit values and quality objectives for mercury discharges by sectors other than the chlor-alkali electrolysis industry.
84/491/EEC	On limit values and quality objectives for discharges of hexachlorocyclohexane.
86/280/EEC	On limit values and quality objectives for discharges of certain dangerous substances included in List I of the Annex to Directive 76/464/EEC.
88/347/EEC	Amending Annex II to Directive 86/280/EEC on limit values and quality objectives for discharges of certain dangerous substances included in List I of the Annex to Directive 76/464/EEC.
90/415/EEC	Amending Annex II to Directive 86/280/EEC on limit values and quality objectives for discharges of certain dangerous substances included in List I of the Annex to Directive 76/464/EEC.

Box 12.7: List I substances

Substances with List I status under Directive 76/464/EEC as a result of the daughter directives shown in Box 12.6.

	Directive Number	Date of entry into force
Aldrin, Dieldrin, Endrin and Isodrin	88/347	1/1/89
Cadmium and its compounds	83/513	1/4/86
Carbon tetrachloride	86/280	1/1/88
Chloroform	88/347	1/1/90
DDT (all isomers)	86/280	1/1/88
Hexachlorobenzene	88/347	1/1/90
Hexachlorobutadiene	88/347	1/1/90
Hexachlorocyclohexane (all isomers)	84/491	1/4/86
Mercury and its compounds:		
Chlor-alkali	82/176	1/7/83
Other sectors	84/156	12/3/86
Pentachlorophenol	86/280	1/1/88
1,2-Dichloroethane	90/415	1/1/93
Trichloroethylene	90/415	1/1/93
Tetrachloroethylene	90/415	1/1/93
Trichlorobenzene (1,2,4 & technical blends.)	90/415	1/1/93

There are around 4,500 potential List I substances used within the European Community. In 1982 the Commission selected 129 of these substances for priority inclusion in List I. This priority list now contains 109 substances, including organochlorines, PCBs, aromatic solvents and several pesticides, though it is still known as the 'List of 129'.[85]

For List I substances emission limit values and quality objectives are set on a Community-wide basis by the daughter directives. Implementation by Member States is through a system of prior authorisations for discharges. In contrast, control of List II substances is at a national level. Member States are required to implement pollution reduction programmes for substances belonging to the families and groups of substances in List II which have a deleterious effect on the environment. The selection of such substances, and setting of appropriate quality objectives is a matter for Member States.

Under the Groundwater Directive procedures must be established for prior investigation followed by authorisation or prohibition of all discharges, disposal or tipping of List II substances and indirect discharges of List I substances. Indirect discharges involve percolation through ground or subsoil before introduction into groundwater. Direct discharges of List I substances are prohibited unless investigation has shown that the receiving groundwater is permanently unsuitable for other uses, as may be the case in long established industrial areas. Discharges of trace amounts of List I and List II substances, which will not cause any deterioration in groundwater quality, may be permitted. The Groundwater Directive seeks to conserve groundwater resources and applies to all groundwater, irrespective of current use.

12.6.3 Directives specifying water quality standards

There are five directives which specify standards for water for various uses, or for the support of various types of aquatic life. These directives are listed in Box 12.8. The relevance of these directives to reclamation is that they provide standards for evaluating whether or not water is polluted, and thus whether it requires remedial treatment on site.

All directives except 80/778/EEC, on water for human consumption, specify two types of values: mandatory, 'imperative' (I) values, and non-binding, 'guide' G values. The directives specify sampling and analytical procedures and the percentage of samples which must conform to each

Box 12.8: Directives specifying standards for water.

75/440/EEC	concerning the quality required of surface water intended for the abstraction of drinking water in the Member States.
76/160/EEC	concerning the quality of bathing water.
78/659/EEC	on the quality of fresh waters needing protection or improvement in order to support fish life.
79/923/EEC	on the quality required of shellfish waters.
80/778/EEC	relating to the quality of water intended for human consumption.

value. The Surface Water for Drinking Directive, 75/440/EEC specifies G and I values for three categories of surface water (A1, A2, A3) and the type of treatment required for each category. Directive 78/659/EEC on freshwater for fish applies to surface waters designated by Member States as needing protection or improvement in order to support fish life. There are separate G and I values for waters supporting salmonid and cyprinid fish. Member states are required to implement pollution reduction programmes to ensure that waters conform to I values within five years of their designation. The G and I values given in these directives, which are relevant to land reclamation, are shown in Table 12.4 and 12.5.

In contrast to the other directives the standards in directive 80/778/EEC, on water for human consumption, are referred to as guide levels (GL) and maximum admissible concentrations (MAC). These have been defined for a wide range of parameters and are often used when interpreting results of groundwater analyses. GL and MAC values for parameters of relevance to land reclamation are shown in Table 12.7.

12.6.4 Other standards

In addition to Community-wide standards laid down by EC directives individual Member States may have set quality objectives for List II substances under the Dangerous Substances Directive, 76/464/EEC.

Standards for contaminated land may also include standards for water quality. The Dutch list (see Section 2.6.5) gives the most complete coverage in terms of range of parameters for groundwater quality. A study for the Department of the Environment in the UK on the redevelopment of gas works and similar sites recommends threshold trigger values in water samples for phenols, free cyanide, thiocyanate and sulphide.[86] These trigger values are shown in Table 12.8.

Table 12.4: G and I values specified in Directive 75/440/EEC on Surface water for drinking.

Parameter	Unit	A1 G	A1 I	A2 G	A2 I	A3 G	A3 I
pH		6.5-8.5		5.5-9		5.5-9	
Total suspended solids	mg/l SS	25					
Conductivity	µS/cm^{-1} at 20°C	1000		1000		1000	
Nitrates	mg/l NO$_3$	25	50*		50*		50*
Fluorides	mg/l F	0.7-1	1.5	0.7-1.7		0.7-1.7	
Dissolved iron	mg/l Fe	0.1	0.3	1	2	1	
Manganese	mg/l Mn	0.05		0.1		1	
Copper	mg/l Cu	0.02	0.05	0.05		1	
Zinc	mg/l Zn	0.5	3	1	5	1	5
Boron	mg/l B	1		1		1	
Arsenic	mg/l As	0.01	0.05		0.05	0.05	0.1
Cadmium	mg/l Cd	0.001	0.005	0.001	0.005	0.001	0.005
Total chromium	mg/l Cr		0.05		0.05		0.05
Lead	mg/l Pb		0.05		0.05		0.05
Selenium	mg/l Se		0.01		0.01		0.01
Mercury	mg/l Hg	0.0005	0.001	0.0005	0.001	0.0005	0.001
Barium	mg/l Ba		0.1		1		1
Cyanide	mg/l CN		0.05		0.05		0.05
Sulphates	mg/l SO$_4$	150	250	150	250*	150	250*

Categories of treatment :
A1 simple physical treatment and disinfection
A2 physical treatment, chemical treatment and disinfection
A3 intensive physical and chemical treatment, extended treatment and disinfection

Table 12.4 continued:

Parameter	Unit	A1 G	A1 I	A2 G	A2 I	A3 G	A3 I
Chlorides	mg/l Cl	200		200		200	
Phosphates	mg/l P_2O_5	0.4		0.7		0.7	
Phenols (phenol index)	mg/l C_6H_5OH		0.001	0.001	0.005	0.01	0.1
Dissolved or emulsified hydrocarbons (after extraction by petroleum ether)	mg/l		0.05		0.2	0.5	1
PAH	mg/l		0.0002		0.0002		1.0001
Total pesticides †	mg/l		0.001		0.0025		0.005
COD	mg/l O_2					30	
Dissolved oxygen saturation rate	% O_2	>70		<50		<30	
BOD_5	mg/l O_2	<3		<5		<7	
Nitrogen by Kjeldahl method (except NO_3)	mg/l N	1		2		3	
Ammonia	mg/l NH_4	0.05		1	1.5	2	4 ‡
Substances extractable with chloroform	mg/l SEC	0.1		0.2		0.5	

PAH	Polycyclic aromatic hydrocarbons
†	Parathion, BHC, dieldrin
‡	exceptional climatic or geographical conditions
COD	Chemical oxygen demand
BOD_5	Biochemical oxygen demand (at 20°C without nitrification)

Table 12.5: G and I values specified in Directive 78/659/EEC on freshwater for fish

Parameter	Salmonid waters		Cyprinid waters		Comments
	G	I	G	I	
pH		6 to 9		6 to 9	
Suspended solids (mg/l)	525		525		Values do not apply to suspended solids with harmful properties.
BOD$_5$ (mg/l)	53		56		
Nitrites (mg/l NO$_2$)	≤0.01		≤0.03		
Phenolic compounds (mg/l C_6H_5OH)		2		3	Inspection by taste
Petroleum hydrocarbons		3		3	Inspection by visual appearance and taste
Non-ionised ammonia (mg/l NH$_4$)	≤0.005	≤0.005	≤0.005	≤0.005	
Total ammonium (mg/l NH$_4$)	≤0.04	≤1	≤0.2	≤1	
Total residual chlorine (mg/l HOCl)		≤0.005		≤0.005	Higher values can be accepted if pH>6
Total zinc (mg/l Zn)		≤0.3		≤1.0	See Table 12.6
Dissolved copper (mg/l Cu)	≤0.04		≤0.04		See Table 12.6

Table 12.6: Variation of copper and zinc limit values with water hardness.

		Water hardness (mg/l CaCO$_3$)				
		10	50	100	300	500
Zinc I values:	salmonid waters (mg/l total Zn)	0.03	0.2	0.3		0.5
	cyprinid waters (mg/l total Zn)	0.3	0.7	1.0		2.0
Copper G values:	(mg/l dissolved Cu)	0.005	0.022	0.04	0.112	

Table 12.7: GL and MAC values specified in Directive 80/778/EEC on water for human consumption.

Parameters	Units	Guide level (GL)	MAC	Comments
Hydrogen ion concentration	pH unit	6.5 ≤ pH ≤ 8.5		- The water should not be aggressive. - The pH values do not apply to water in closed containers. - Maximum admissible value: 9.5.
Conductivity	μS cm^{-1} at 20°C	400		- Corresponding to the mineralisation of the water. - Corresponding relativity values in ohms/cm: 2500.
Chlorides	mg/l Cl	25		- Approximation concentration above which effects might occur: 200mg/l
Sulphates	mg/l SO_4	25	250	
Calcium	mg/l Ca	100		
Magnesium	mg/l Mg	30	50	
Sodium	mg/l Na	20	175	- As from 1984 and with a percentile of 90.
			150	- As from 1987 and with a percentile of 80. These percentiles should be calculated over a reference period of three years.
Potassium	mg/l K	10	12	
Aluminium	mg/l Al	0.05	0.2	
Free carbon dioxide	mg/l CO_2			- The water should not be aggressive.
Nitrates	mg/l NO_3	25	50	
Nitrites	mg/l NO_2		0.1	
Ammonium	mg/l NH_4	0.05	0.5	
Kjeldahl Nitrogen †	mg/l N		1	
($KMnO_4$) Oxidisability	mg/l O_2	2	5	- Measured when heated in acid medium.
Substances extractable in chloroform	mg/l dry residue	0.1		
Dissolved or emulsified hydrocarbons ‡	mg/l	10		
Phenols (phenol index)	C_6H_5OH mg/l		0.5	- Excluding natural phenols which do not react with chlorine.

Table 12.7 continued

Parameters	Units	Guide level (GL)	MAC	Comments
Boron	mg/l B		1000	
Iron	mg/l Fe	50	200	
Manganese	mg/l Mn	20	50	
Copper	mg/l Cu	100		- Above 3000 μg/l astringent taste, discolouration + corrosion may occur.
Zinc	mg/l Zn	100		
Phosphorus	mg/l P_2O_5	400	5000	
Fluoride	mg/l F			
	8-12 °C		1500	- MAC varies according to average temperature in geographical area concerned.
	25-30 °C		700	
Arsenic	mg/l As		50	
Cadmium	mg/l Cd		5	
Cyanides	mg/l CN		50	
Chromium	mg/l Cr		50	
Mercury	mg/l Hg		1	
Nickel	mg/l Ni		50	
Lead	mg/l Pb		50	
Antimony	mg/l Sb		10	
Selenium	mg/l Se		10	
Pesticides	mg/l			- Includes PCBs and PCTs
- individual compounds			0.1	
- total			0.5	
Other organochlorine compounds	mg/l mg/l	1		- Haloform concentrations must be as low as possible.
PAH			0.2	

† excluding N in NO_2 and NO_3
‡ after extraction by petroleum ether.
PAH polyaromatic hydrocarbons

Table 12.8: Tentative trigger values for substances in samples of water from former gas works sites (from Environmental Resources Limited, 1987[86])

Parameter	Units	Threshold trigger value	Action trigger value
Phenols	mg/l	1	20
Free cyanide	mg/l	5	50
Thiocyanate	mg/l	5*	NL
Sulphide	mg/l	5	50

* If any water sample has a red coloration the threshold value is exceeded

NL No limit set

These trigger values apply to all site end-uses.