

Treatment methods and performance

A5.1 Treatment methods

A5.1.1 Chlorination

Chlorination can be achieved by using liquefied chlorine gas, sodium hypochlorite solution or calcium hypochlorite granules and on-site chlorine generators. Liquefied chlorine gas is supplied in pressurized containers. The gas is withdrawn from the cylinder and dosed into water by a chlorinator, which both controls and measures the gas flow rate. Sodium hypochlorite solution is dosed using a positive-displacement electric dosing pump or gravity feed system. Calcium hypochlorite has to be dissolved in water, then mixed with the main supply. Chlorine, whether in the form of chlorine gas from a cylinder, sodium hypochlorite or calcium hypochlorite, dissolves in water to form hypochlorous acid (HOCl) and hypochlorite ion (OCl^-).

Different techniques of chlorination can be used, including breakpoint chlorination, marginal chlorination and superchlorination/dechlorination. Breakpoint chlorination is a method in which the chlorine dose is sufficient to rapidly oxidize all the ammonia nitrogen in the water and to leave a suitable free residual chlorine available to protect the water against reinfection from the point of chlorination to the point of use. Superchlorination/dechlorination is the addition of a large dose of chlorine to effect rapid disinfection and chemical reaction, followed by reduction of excess free chlorine residual. Removing excess chlorine is important to prevent taste problems. It is used mainly when the bacterial load is variable or the detention time in a tank is not enough. Marginal chlorination is used where water supplies are of high quality and is the simple dosing of chlorine to produce a desired level of free residual chlorine. The chlorine demand in these supplies is very low, and a breakpoint might not even occur.

Chlorination is employed primarily for microbial disinfection. However, chlorine also acts as an oxidant and can remove or assist in the removal or chemical conversion of some chemicals—for example, decomposition of easily oxidized pesticides, such as aldicarb; oxidation of dissolved species (e.g. manganese(II)) to form insoluble products that can be removed by subsequent filtration; and oxidation of dissolved species to more easily removable forms (e.g. arsenite to arsenate).

A disadvantage of chlorine is its ability to react with natural organic matter to produce trihalomethanes and other halogenated disinfection by-products. However, by-product formation may be controlled by optimization of the treatment system.

A5.1.2 Ozonation

Ozone is a powerful oxidant and has many uses in water treatment, including oxidation of organic chemicals. Ozone can be used as a primary disinfectant. Ozone gas (O_3) is formed by passing dry air or oxygen through a high-voltage electric field. The resultant ozone-enriched air is dosed directly into the water by means of porous diffusers at the base of baffled contactor tanks. The contactor tanks, typically about 5 m deep, provide 10–20 minutes of contact time. Dissolution of at least 80% of the applied ozone should be possible, with the remainder contained in the off-gas, which is passed through an ozone destructor and vented to the atmosphere.

The performance of ozonation relies on achieving the desired concentration after a given contact period. For oxidation of organic chemicals, such as some oxidizable pesticides, a residual of about 0.5 mg/l after a contact time of up to 20 minutes is typically used. The doses required to achieve this vary with the type of water but are typically in the range 2–5 mg/l. Higher doses are needed for untreated waters, because of the ozone demand of the natural background organics.

Ozone reacts with natural organics to increase their biodegradability, measured as assimilable organic carbon. To avoid undesirable bacterial growth in distribution, ozonation is normally used with subsequent treatment, such as biological filtration or granular activated carbon (GAC), to remove biodegradable organics, followed by a chlorine residual, as ozone does not provide a disinfectant residual. Ozone is effective for the degradation of a wide range of pesticides and other organic chemicals.

A5.1.3 Other disinfection processes

Other disinfection methods include chloramination, the use of chlorine dioxide and UV radiation, as well as alternative disinfection techniques that may be used in smaller-scale applications, such as for household water.

Chloramines (monochloramine, dichloramine and trichloramine, or nitrogen trichloride) are produced by the reaction of aqueous chlorine with ammonia. Monochloramine is the only useful chloramine disinfectant, and conditions employed for chloramination are designed to produce only monochloramine. Monochloramine is a less effective disinfectant than free chlorine, but it is persistent, and it is therefore an attractive secondary disinfectant for the maintenance of a stable distribution system residual.

Chlorine dioxide has been used in recent years because of concerns about disinfection by-product production associated with chlorine disinfection. Typically, chlorine dioxide is generated immediately prior to application by the addition of chlorine gas or an aqueous chlorine solution to aqueous sodium chlorite. Chlorine dioxide decomposes in water to form chlorite and chlorate.

UV radiation, emitted by a low-pressure or medium-pressure mercury arc lamp, is biocidal between wavelengths of 180 and 320 nm. It can be used to inactivate protozoa, bacteria, bacteriophage, yeast, viruses, fungi and algae. Turbidity can inhibit UV

disinfection. UV radiation can act as a catalyst in oxidation reactions when used in conjunction with ozone or hydrogen peroxide.

Numerous possible disinfection techniques are being developed and are typically used in smaller-scale applications, such as household point-of-use and point-of-entry water treatment systems. Some of these, including bromine and iodine, show promise for expanded use. Bromine and iodine are halogens, like chlorine, and they are well-known biocides. Iodine is commonly used for short-term applications, such as by travellers in areas where water quality is questionable. Some forms of silver may have applications as bacteriostats or possibly as slow-acting disinfectants for some microorganisms; however, there are not good peer-reviewed published data to quantify the latter. It will be necessary to develop a more thorough analysis of the biocidal efficacy, potential disinfection by-products and risks from long-term exposures and application conditions for these lesser-used treatment chemicals to provide appropriate guidance as to their potential for wider applications.

A5.1.4 Filtration

Particulate matter can be removed from raw waters by rapid gravity, horizontal, pressure or slow sand filters. Slow sand filtration is essentially a biological process, whereas the others are physical treatment processes.

Rapid gravity, horizontal and pressure filters can be used for filtration of raw water, without pretreatment. Rapid gravity and pressure filters are commonly used to filter water that has been pretreated by coagulation and sedimentation. An alternative process is direct filtration, in which coagulation is added to the water, which then passes directly onto the filter where the precipitated floc (with contaminants) is removed; the application of direct filtration is limited by the available storage within the filter to accommodate solids.

Rapid gravity filters

Rapid gravity sand filters usually consist of open rectangular tanks (usually < 100 m²) containing silica sand (size range 0.5–1.0 mm) to a depth of between 0.6 and 2.0 m. The water flows downwards, and solids become concentrated in the upper layers of the bed. The flow rate is generally in the range 4–20 m³/m²·h. Treated water is collected via nozzles in the floor of the filter. The accumulated solids are removed periodically by backwashing with treated water, sometimes preceded by scouring of the sand with air. A dilute sludge that requires disposal is produced.

In addition to single-medium sand filters, dual-media or multimedia filters are used. Such filters incorporate different materials, such that the structure is from coarse to fine as the water passes through the filter. Materials of suitable density are used in order to maintain the segregation of the different layers following backwashing. A common example of a dual-media filter is the anthracite–sand filter, which typically consists of a 0.2 m deep layer of 1.5 mm anthracite over a 0.6 m deep layer of silica sand. Anthracite, sand and garnet can be used in multimedia filters. The advantage of dual-media and multimedia filters is that there is more efficient use of the whole bed depth for particle retention—the rate of headloss development can be half that of

single-medium filters, which can allow higher flow rates without increasing headloss development.

Rapid gravity filters are most commonly used to remove floc from coagulated waters (see [section A5.1.6](#)). They may also be used to reduce turbidity (including adsorbed chemicals) and oxidized iron and manganese from raw waters.

Roughing filters

Roughing filters can be applied as pre-filters prior to other processes such as slow sand filters. Roughing filters with coarse gravel or crushed stones as the filter medium can successfully treat water of high turbidity (> 50 nephelometric turbidity units). The main advantage of roughing filtration is that as the water passes through the filter, particles are removed by both filtration and gravity settling. Horizontal filters can be up to 10 m long and are operated at filtration rates of $0.3\text{--}1.0\text{ m}^3/\text{m}^2\cdot\text{h}$.

Pressure filters

Pressure filters are sometimes used where it is necessary to maintain head in order to eliminate the need for pumping into supply. The filter bed is enclosed in a cylindrical shell. Small pressure filters, capable of treating up to about $15\text{ m}^3/\text{h}$, can be manufactured in glass-reinforced plastics. Larger pressure filters, up to 4 m in diameter, are manufactured in specially coated steel. Operation and performance are generally as described for the rapid gravity filter, and similar facilities are required for backwashing and disposal of the dilute sludge.

Slow sand filters

Slow sand filters usually consist of tanks containing sand (effective size range $0.15\text{--}0.3\text{ mm}$) to a depth of between 0.5 and 1.5 m. The raw water flows downwards, and turbidity and microorganisms are removed primarily in the top few centimetres of the sand. A biological layer, known as the “schmutzdecke”, develops on the surface of the filter and can be effective in removing microorganisms. Treated water is collected in underdrains or pipework at the bottom of the filter. The top few centimetres of sand containing the accumulated solids are removed and replaced periodically. Slow sand filters are operated at a water flow rate of between 0.1 and $0.3\text{ m}^3/\text{m}^2\cdot\text{h}$.

Slow sand filters are more suitable for low-turbidity water or water that has been pre-filtered. They are used to remove algae and microorganisms, including protozoa, and, if preceded by microstraining or coarse filtration, to reduce turbidity (including adsorbed chemicals). Slow sand filtration is effective for the removal of some organics, including certain pesticides and also ammonia.

Bank filtration

Bank filtration is a process that produces an influx of surface water through the groundwater, via the bed and banks of the surface water body. This is commonly achieved through abstraction from boreholes adjacent to the surface water source. It is a relatively simple and low-cost means for removing particulates and microorganisms from surface water by placing pumping wells in alluvial sediments of the river or stream banks. The sediments act as both a filter and biofilter, trapping and reducing the concentrations of microorganisms and many organic pollutants. Bank filtration wells can

be either horizontal or vertical, depending upon the hydrogeological circumstances and required production rate. Horizontal wells are often used where alluvial deposits are shallow or where high pumping rates are required.

Bank filtration can remove particles, bacteria, viruses, parasites, heavy metals and easily biodegradable compounds. Bank filtration attenuates concentration peaks, providing uniform quality of raw water feed to downstream treatment. The performance of bank filtration can be highly dependent upon several factors, including soil and geological conditions as well as the quality of the source water. Bank filters can become clogged, resulting in pressure drops. Site-specific testing is needed to determine whether the appropriate geology is present as well as the effectiveness and operational parameters.

A5.1.5 Aeration

Aeration processes are designed to achieve removal of gases and volatile compounds by air stripping. Transfer can usually be achieved using a simple cascade or diffusion of air into water, without the need for elaborate equipment. Stripping of gases or volatile compounds, however, may require a specialized plant that provides a high degree of mass transfer from the liquid phase to the gas phase.

Cascade or step aerators are designed so that water flows in a thin film to achieve efficient mass transfer. Cascade aeration may introduce a significant headloss; design requirements are between 1 and 3 m to provide a loading of 10–30 m³/m²·h. Alternatively, compressed air can be diffused through a system of submerged perforated pipes. These types of aerator are used for oxidation and precipitation of iron and manganese.

Air stripping can be used for removal of volatile organics (e.g. solvents), some taste- and odour-causing compounds and radon. Aeration processes to achieve air stripping need to be much more elaborate to provide the necessary contact between the air and water. The most common technique is cascade aeration, usually in packed towers in which water is allowed to flow in thin films over plastic media with air blown counter-current. The required tower height and diameter are functions of the volatility and concentration of the compounds to be removed and the flow rate. Increasing the dissolved oxygen content of a water can increase its corrosivity towards some metallic materials used in distribution pipes and plumbing, and this should be taken into account when considering aeration as a treatment process.

A5.1.6 Chemical coagulation

Chemical coagulation-based treatment is the most common approach for treatment of surface waters and is almost always based on the following unit processes.

Chemical coagulants, usually salts of aluminium or iron, are dosed to the raw water under controlled conditions to form a solid flocculent metal hydroxide. Typical coagulant doses are 2–5 mg/l as aluminium or 4–10 mg/l as iron. The precipitated floc removes suspended and dissolved contaminants by mechanisms of charge neutralization, adsorption and entrapment. The efficiency of the coagulation process depends on raw water quality, the coagulant or coagulant aids used and operational factors, including mixing conditions, coagulation dose and pH. The floc is removed from the

treated water by subsequent solid–liquid separation processes such as sedimentation or flotation and/or rapid or pressure gravity filtration.

Effective operation of the coagulation process depends on selection of the optimum coagulant dose and also the pH value. The required dose and pH can be determined by using small-scale batch coagulation tests, often termed “jar tests”. Increasing doses of coagulant are applied to raw water samples that are stirred and allowed to settle. The optimum dose is selected as that which achieves adequate removal of colour and turbidity; the optimum pH can be selected in a similar manner. These tests have to be conducted at a sufficient frequency to keep pace with changes in raw water quality and hence coagulant demand.

Powdered activated carbon (PAC) may be dosed during coagulation to adsorb organic chemicals, such as some hydrophobic pesticides. The PAC will be removed as an integral fraction of the floc and disposed of with the waterworks sludge.

The floc may be removed by sedimentation to reduce the solids loading to the subsequent rapid gravity filters. Sedimentation is most commonly achieved in horizontal flow or floc blanket clarifiers. Alternatively, floc may be removed by dissolved air flotation, in which solids are contacted with fine bubbles of air that attach to the floc, causing them to float to the surface of the tank, where they are removed periodically as a layer of sludge. The treated water from either process is passed to rapid gravity filters (see [section A5.1.4](#)), where remaining solids are removed. Filtered water may be passed to a further stage of treatment, such as additional oxidation and filtration (for removal of manganese), ozonation and/or GAC adsorption (for removal of pesticides and other trace organics), prior to final disinfection before the treated water enters the supply.

Coagulation is suitable for removal of particulates and bound microorganisms, certain heavy metals and low-solubility organic chemicals, such as certain organo-chlorine pesticides. For other organic chemicals, coagulation is generally ineffective, except where the chemical is bound to humic material or adsorbed onto particulates.

A5.1.7 Activated carbon adsorption

Activated carbon is produced by the controlled thermalization of carbonaceous material, normally wood, coal, coconut shells or peat. This activation produces a porous material with a large surface area (500–1500 m²/g) and a high affinity for organic compounds. It is normally used in either powdered (PAC) or granular (GAC) form. When the adsorption capacity of the carbon is exhausted, it can be reactivated by burning off the organics in a controlled manner. However, PAC (and some GAC) is normally used only once before disposal. Different types of activated carbon have different affinities for types of contaminants.

The choice between PAC and GAC will depend upon the relative cost-effectiveness, frequency and dose required. PAC would generally be preferred in the case of seasonal or intermittent contamination or where low dosage rates are required.

PAC is dosed as a slurry into the water and removed by subsequent treatment processes, together with the waterworks sludge. Its use is therefore restricted to surface water treatment works with existing filters. GAC in fixed-bed adsorbers is used much more efficiently than PAC dosed into the water, and the effective carbon use per water

volume treated would be much lower than the dose of PAC required to achieve the same removal.

GAC is used for taste and odour control. It is normally used in fixed beds, either in purpose-built adsorbers for chemicals or in existing filter shells by replacement of sand with GAC of a similar particle size. Although at most treatment works it would be cheaper to convert existing filters rather than build separate adsorbers, use of existing filters usually allows only short contact times, and they are not capable of facile reactivation. It is therefore common practice to install additional GAC adsorbers (in some cases preceded by ozonation) between the rapid gravity filters and final disinfection. Most groundwater sources do not have existing filters, and separate adsorbers would need to be installed.

The service life of a GAC bed is dependent on the capacity of the carbon used and the contact time between the water and the carbon, the empty bed contact time, controlled by the flow rate of the water. Empty bed contact times are usually in the range 5–30 minutes. GACs vary considerably in their capacity for specific organic compounds, which can have a significant effect upon their service life. A guide to capacity can be obtained from published isotherm data. Carbon capacity is strongly dependent on the water source and is greatly reduced by the presence of background organic compounds. The properties of a chemical that influence its adsorption onto activated carbon include the water solubility and octanol–water partition coefficient. As a general rule, chemicals with low solubilities and high log octanol–water partition coefficients are well adsorbed.

Activated carbon is used for the removal of pesticides and other organic chemicals, taste and odour compounds, cyanobacterial toxins and total organic carbon.

A5.1.8 Ion exchange

Ion exchange is a process in which ions of like charge are exchanged between the water phase and the solid resin phase. Water softening is achieved by cation exchange. Water is passed through a bed of cationic resin, and the calcium ions and magnesium ions in the water are replaced by sodium ions. When the ion exchange resin is exhausted (i.e. the sodium ions are depleted), it is regenerated using a solution of sodium chloride. The process of “dealkalization” can also soften water. Water is passed through a bed of weakly acidic resin, and the calcium and magnesium ions are replaced by hydrogen ions. The hydrogen ions react with the carbonate and bicarbonate ions to produce carbon dioxide. The hardness of the water is thus reduced without any increase in sodium levels. Anion exchange can be used to remove contaminants such as nitrate, fluoride, arsenate and uranium (as the uranyl anion), which are exchanged for chloride. Several appropriate resins are available for this purpose.

An ion exchange plant normally consists of two or more resin beds contained in pressure shells with appropriate pumps, pipework and ancillary equipment for regeneration. The pressure shells are typically up to 4 m in diameter, containing 0.6–1.5 m depth of resin.

Cation exchange can be used for removal of certain heavy metals. Potential applications of anionic resins, in addition to nitrate removal, are for removal of arsenic and selenium species.

A5.1.9 Membrane processes

The membrane processes of most significance in water treatment are reverse osmosis, ultrafiltration, microfiltration and nanofiltration. These processes have traditionally been applied to the production of water for industrial or pharmaceutical applications, but are now being applied to the treatment of drinking-water.

High-pressure processes

If two solutions are separated by a semipermeable membrane (i.e. a membrane that allows the passage of the solvent but not of the solute), the solvent will naturally pass from the lower-concentration solution to the higher-concentration solution. This process is known as osmosis. It is possible, however, to force the flow of solvent in the opposite direction, from the higher to the lower concentration, by increasing the pressure on the higher-concentration solution. The required pressure differential is known as the osmotic pressure, and the process is known as reverse osmosis.

Reverse osmosis results in the production of a treated water stream and a relatively concentrated waste stream. Typical operating pressures are in the range 15–50 bar, depending on the application. Reverse osmosis rejects monovalent ions and organics of molecular weight greater than about 50 daltons (membrane pore sizes are less than 0.002 μm). The most common application of reverse osmosis is desalination of brackish water and seawater.

Nanofiltration uses a membrane with properties between those of reverse osmosis and ultrafiltration membranes; pore sizes are typically 0.001–0.01 μm . Nanofiltration membranes allow monovalent ions such as sodium or potassium to pass but reject a high proportion of divalent ions such as calcium and magnesium and some higher molecular weight organics. Operating pressures are typically about 5 bar. Nanofiltration may be effective for the removal of colour-forming organic compounds.

Lower-pressure processes

Ultrafiltration is similar in principle to reverse osmosis, but the membranes have much larger pore sizes (typically 0.002–0.03 μm) and operate at lower pressures. Ultrafiltration membranes reject organic molecules of molecular weight above about 800 daltons and usually operate at pressures less than 5 bar.

Microfiltration is a direct extension of conventional filtration into the sub-micrometre range. Microfiltration membranes have pore sizes typically in the range 0.01–12 μm and do not separate molecules but reject colloidal and suspended material at operating pressures of 1–2 bar. Microfiltration is capable of sieving out particles greater than 0.05 μm . It has been used for water treatment in combination with coagulation or PAC to remove particulates and some dissolved organic carbon prior to reverse osmosis membranes and to improve permeate flux.

A5.1.10 Other treatment processes

Processes aimed at generating hydroxyl radicals are known collectively as advanced oxidation processes and can be effective for the destruction of chemicals that are difficult to treat using other methods, such as ozone alone. Hydrogen peroxide with UV is also a source of hydroxyl radicals. Chemicals can react either directly with molecular

ozone or with the hydroxyl radical ($\text{HO}\cdot$), which is a product of the decomposition of ozone in water and is an exceedingly powerful indiscriminate oxidant that reacts readily with a wide range of organic chemicals. The formation of hydroxyl radicals can be encouraged by using ozone at high pH. One advanced oxidation process using ozone or UV plus hydrogen peroxide involves dosing hydrogen peroxide simultaneously with ozone at a rate of approximately 0.4 mg of hydrogen peroxide per litre per milligram of ozone dosed per litre (the theoretical optimum ratio for hydroxyl radical production) and bicarbonate.

Other treatment processes that can be used in certain applications include:

- precipitation softening (addition of lime, lime plus sodium carbonate or sodium hydroxide to precipitate hardness at high pH);
- ion exchange softening;
- biological denitrification for removal of nitrate from surface waters;
- biological nitrification for removal of ammonia from surface waters;
- activated alumina (or other adsorbents) for specialized applications, such as removal of fluoride and arsenic.

A5.2 Treatment performance for chemicals for which guideline values have been established

Treatment performance for chemicals for which guideline values have been established is given in [Tables A5.1–A5.5](#).

A5.3 Corrosion of metals used in water treatment and distribution

A5.3.1 Brass

The main corrosion problem with brasses is dezincification, which is the selective dissolution of zinc from duplex brass, leaving behind copper as a porous mass of low mechanical strength. Meringue dezincification, in which a voluminous corrosion product of basic zinc carbonate forms on the brass surface, largely depends on the ratio of chloride to alkalinity. Meringue dezincification can be controlled by maintaining a low zinc to copper ratio (1:3 or lower) and by keeping pH below 8.3.

General dissolution of brass can also occur, releasing metals, including lead, into the water. Impingement attack can occur under conditions of high water velocity with waters that form poorly protective corrosion product layers and that contain large amounts of dissolved or entrained air.

A5.3.2 Concrete and cement

Concrete is a composite material consisting of a cement binder in which an inert aggregate is embedded. Cement is primarily a mixture of calcium silicates and aluminates together with some free lime. Cement mortar, in which the aggregate is fine sand, is used as a protective lining in iron and steel water pipes. In asbestos–cement pipe, the aggregate is asbestos fibres, which are not of concern in drinking-water (see also asbestos fact sheet in [chapter 12](#)). Cement is subject to deterioration on prolonged exposure to aggressive water, due either to the dissolution of lime and other soluble compounds

Table A5.1 Treatment performance for naturally occurring chemicals for which guideline values have been established^{a,b}

	Coagulation	Ion exchange	Precipitation softening	Activated alumina	Activated carbon	Ozonation	Adsorption/oxidation	Membranes
Arsenic ^c	++ <0.005	+++ <0.005	++ <0.005	+++ <0.005				+++ ^d <0.005
Fluoride	++			+++ <1				+++ <1
Manganese		++ ^e <0.05	+++ <0.02			++ ^f <0.05	+++ ^g <0.02	+++ ^h <0.01
Selenium	++	+++ <0.01		+++ <0.01				+++ <0.01
Uranium	++	+++ <0.001	++	+++ <0.001				

^a Symbols are as follows:

++ Approximately 50% or more removal

+++ Approximately 80% or more removal

^b The table includes chemicals for which some treatment data are available. A blank entry in the table indicates either that the process is completely ineffective or that there are no data on the effectiveness of the process. For the most effective processes, the table estimates the concentration of the chemical (in mg/l) that could be achievable in an ideal water.^c Iron oxide-based and iron hydroxide-based media have been shown to be very effective for both arsenate and arsenite forms.^d Reverse osmosis membranes are more effective for removal of arsenate than arsenite. However, arsenite is readily oxidized to arsenate by disinfectants (e.g. chlorine).^e Dissolved manganese(II) can be removed through cation exchange in zeolite softening processes.^f Oxidation of manganese using ozone must be followed by a filtration step.^g Includes manganese greensand and other filter media coated with manganese oxides (such as conventional filtration media with free chlorine applied across the filter bed).^h Low pressure membrane filtration preceded by oxidation using potassium permanganate.

Table A5.2 Treatment performance for chemicals from industrial sources and human dwellings for which guideline values have been established^{a,b}

	Air stripping	Coagulation	Ion exchange	Precipitation softening	Activated carbon	Ozonation	Advanced oxidation	Membranes	Biological treatment ^c	UV irradia- tion
Cadmium		+++ <0.002	+++ <0.002	+++ <0.002				+++ <0.002		
Mercury		+++ <0.0001		+++ <0.0001	+++ <0.0001			+++ <0.0001		
Benzene	+++ <0.01				+++ <0.01	+++ <0.01	Yes ^d			
Carbon tetrachloride	+++ <0.001				+++ <0.001			+		
1,2-Dichlorobenzene	+++ <0.01				+++ <0.01	+++ <0.01		Yes ^d		
1,4-Dichlorobenzene	+++ <0.01				+++ <0.01	+++ <0.01		Yes ^d		
1,2-Dichloroethane	+++				+++ <0.01		+			
1,2-Dichloroethene	+++ <0.01				+++ <0.01	+++ <0.01				
1,4-Dioxane					+		+++ 0.05			
Edetic acid					+++ <0.01					
Ethylbenzene	++ <0.001	+			+++ <0.001	+++ <0.001	++	+	++	
Hexachlorobutadiene					+++ <0.001			+		

Table A5.2 (continued)

	Air stripping	Coagulation	Ion exchange	Precipitation softening	Activated carbon	Ozonation	Advanced oxidation	Membranes	Biological treatment ^c	UV irradia- tion
Nitrilotriacetic acid					++				++	
N-Nitrosodimethylamine					+		++			+
Pentachlorophenol					+++ <0.0004			++		
Perchlorate			yes ^d					yes ^d	yes ^d	
Styrene	+++ <0.02				+++ <0.002	++		+	+	
Tetrachloroethene	+++ <0.001				+++ <0.001			+		
Toluene	+++ <0.001				+++ <0.001	+++ <0.001	+++ ^e <0.001		++ <0.001	
Trichloroethene	+++ <0.02				+++ <0.02	+++ <0.02	+++ ^e <0.02			
Xylenes	+++ <0.005				+++ <0.005		+++ ^e <0.005		++	

^a Symbols are as follows:

- + Limited removal
- ++ Approximately 50% or more removal
- +++ Approximately 80% or more removal

^b The table includes only those chemicals for which some treatment data are available. A blank entry in the table indicates either that the process is completely ineffective or that there are no data on the effectiveness of the process. For the most effective processes, where data are available, the table indicates the concentration of the chemical (in mg/l) that should be achievable.

^c Biological treatment includes slow sand filtration and bank filtration.

^d Yes means known or likely to be effective, but performance was not quantified.

^e Might be effective, but other techniques would be more likely to be applied due to cost.

Table A5.3 Treatment performance for chemicals from agricultural activities for which guideline values have been established^{a,b}

	Chlorination	Air stripping	Coagulation	Ion exchange	Activated carbon	Ozonation	Advanced oxidation	Membranes	Biological treatment ^c
Nitrate				+++ <5				+++ <5	+++ <5
Nitrite	+++ <0.1							+	+++
Alachlor					+++ <0.001	++	+++ <0.001	+++ <0.001	
Aldicarb					+++ <0.001	+++ <0.001		+++ <0.001	
Aldrin/dieldrin			+		+++ <0.000 02	++ <0.000 02		+++ <0.00002	
Atrazine and its chloro-s-triazine metabolites			+		+++ <0.0001	Yes ^d	+++ <0.0001	+++ <0.0001	+++ ^e <0.0001
Carbofuran	+				+++ <0.001	Yes ^d		+++ <0.001	
Chlordane					+++ <0.0001	++ <0.0001		Yes ^d	
Chlorotoluron					+++ <0.0001	+++ <0.0001			
Cyanazine					+++ <0.0001	+		+++ <0.0001	
2,4-D					+++ <0.001	+++ <0.001		Yes ^d	
1,2-Dibromo-3-chloropropane		++ <0.001			+++ <0.0001				

Table A5.3 (continued)

	Chlorination	Air stripping	Coagulation	Ion exchange	Activated carbon	Ozonation	Advanced oxidation	Membranes	Biological treatment ^c
1,2-Dibromoethane		+++ <0.0001			+++ <0.0001				
1,2-Dichloropropane		Yes			+++ <0.001	+			
Dimethoate	+++ <0.001				++	++			
Endrin			+		+++ <0.0002			Yes ^d	
Hydroxyatrazine							+++ <0.001	Yes ^d	
Isoproturon	++				+++ <0.0001	+++ <0.0001	+++ <0.0001	+++ <0.0001	+
Lindane					+++ <0.0001	++		Yes ^d	++
Mecoprop					+++ <0.0001	+++ <0.0001			+++ <0.0001
Methoxychlor			++		+++ <0.0001	+++ <0.0001		Yes ^d	
Metalochlor					+++ <0.0001	++		Yes ^d	++
Simazine					+++ <0.0001	++	+++ <0.0001	+++ <0.0001	
2,4,5-T					+++ <0.001			Yes ^d	

Table A5.3 (continued)

	Chlorination	Air stripping	Coagulation	Ion exchange	Activated carbon	Ozonation	Advanced oxidation	Membranes	Biological treatment ^c
Terbutylazine			+		+++ <0.0001	++			
Trifluralin					+++ <0.0001			+++ ^f <0.0001	

^a Symbols are as follows:

- + Limited removal
- ++ Approximately 50% or more removal
- +++ Approximately 80% or more removal

^b The table includes only those chemicals for which some treatment data are available. A blank entry in the table indicates either that the process is completely ineffective or that there are no data on the effectiveness of the process. For the most effective processes, the table indicates the concentration of the chemical (in mg/l) that should be achievable.

^c Biological treatment includes slow sand filtration, bank filtration and biological denitrification (for nitrate removal).

^d Yes means known or likely to be effective, but performance was not quantified.

^e For bank filtration; slow sand filtration is not effective.

^f Might be effective, but other techniques would be more likely to be applied due to cost.

Table A5.4 Treatment performance for pesticides used in water for public health for which guideline values have been established^{a,b}

	Chlorination	Coagulation	Activated carbon	Ozonation	Advanced oxidation	Membranes
DDT and metabolites		+	+++ <0.0001	+	+++ ^c <0.0001	+++ ^c <0.0001

^a Symbols are as follows:

+ Limited removal

+++ Approximately 80% or more removal

^b For the most effective processes, the table indicates the concentration of the chemical (in mg/l) that should be achievable.

^c Might be effective, but other techniques would be more likely to be applied due to cost.

Table A5.5 Treatment performance for cyanobacterial cells and cyanotoxins for which guideline values or a reference value have been established^{a,b,c}

	Chlorination	Coagulation	Activated carbon	Ozonation	Advanced oxidation	Membranes	Sediment passage ^d
Cyanobacterial cells		+++				+++	+++
Cyanotoxins	+++ ^e		+++	+++	+++	+++ ^f	+++

^a Chlorination, ozonation or advanced oxidation may release cyanotoxins.

^b +++ = 80% or more removal.

^c The table includes only those chemicals for which some treatment data are available. A blank entry in the table indicates either that the process is completely ineffective or that there are no data on the effectiveness of the process.

^d Sediment passage includes slow sand filtration and bank filtration. Note that percolation through soils, such as during artificial groundwater recharge, can also be effective in removing cyanobacteria and cyanotoxins.

^e Not effective for anatoxins.

^f May be effective, depending on pore size and toxin.

or to chemical attack by aggressive ions such as chloride or sulfate, and this may result in structural failure. Newly installed cement materials will leach lime, with consequent increases in pH, alkalinity and hardness. Cement contains a variety of metals that can be leached into the water. Aggressiveness to cement is related to the “aggressivity index”, which has been used specifically to assess the potential for the dissolution of concrete. A pH of 8.5 or higher may be necessary to control cement corrosion.

A5.3.3 Copper

The corrosion of copper pipework and hot water cylinders can cause blue water, blue or green staining of bathroom fittings and, occasionally, taste problems. Copper tubing may be subject to general corrosion, impingement attack and pitting corrosion.

General corrosion is most often associated with soft, acidic waters; waters with pH below 6.5 and hardness of less than 60 mg of calcium carbonate per litre are very aggressive to copper. Copper, like lead, can enter water by dissolution of the corrosion product, basic copper carbonate. The solubility is mainly a function of pH and total inorganic carbon. Solubility decreases with increase in pH, but increases with increase in concentrations of carbonate species. Raising the pH to between 8 and 8.5 is the usual procedure to overcome these difficulties.

Impingement attack is the result of excessive flow velocities and is aggravated in soft water at high temperature and low pH.

The pitting of copper is commonly associated with hard groundwaters having a carbon dioxide concentration above 5 mg/l and high dissolved oxygen. Phosphates have been used to suppress copper corrosion in those cases. Surface waters with organic colour may also be associated with pitting corrosion. Copper pipes can fail by pitting corrosion, which involves highly localized attacks leading to perforations with negligible loss of metal. Two main types of attack are recognized. Type I pitting affects cold water systems (below 40 °C) and is associated, particularly, with hard borehole waters and the presence of a carbon film in the bore of the pipe, derived from the manufacturing process. Tubes that have had the carbon removed by cleaning are immune from Type I pitting. Type II pitting occurs in hot water systems (above 60 °C) and is associated with soft waters. A high proportion of general and pitting corrosion problems are associated with new pipe in which a protective oxide layer has not yet formed. Calcium carbonate precipitation indices such as Langelier and Ryznar are not good predictors of corrosion for copper systems.

A5.3.4 Iron

Iron (either cast or ductile) is frequently used in water distribution systems, and its corrosion is of concern. While structural failure as a result of iron corrosion is rare, water quality problems (e.g. “red water”) can arise as a result of excessive corrosion of iron pipes. The corrosion of iron is a complex process that involves the oxidation of the metal, normally by dissolved oxygen, ultimately to form a precipitate of iron(III). This leads to the formation of tubercles on the pipe surface. The major water quality factors that determine whether the precipitate forms a protective scale are pH and alkalinity. The concentrations of calcium, chloride and sulfate also influence iron corrosion. Successful control of iron corrosion has been achieved by adjusting the pH to

the range 6.8–7.3, hardness and alkalinity to at least 40 mg/l (as calcium carbonate), oversaturation with calcium carbonate of 4–10 mg/l and a ratio of alkalinity to chloride plus sulfate of at least 5 (when both are expressed as calcium carbonate).

Silicates and polyphosphates are often described as “corrosion inhibitors”, but there is no guarantee that they will inhibit corrosion in water distribution systems. However, they can complex dissolved iron (in the iron(II) state) and prevent its precipitation as visibly obvious red “rust”. These compounds may act by masking the effects of corrosion rather than by preventing it. Orthophosphate is a possible corrosion inhibitor and, like polyphosphates, is used to prevent “red water”.

A5.3.5 Lead

Lead corrosion (plumbosolvency) is of particular concern. Lead piping is still common in old houses in some countries, lead solders have been used widely for jointing copper tubing and brass fittings can contain substantial amounts of lead. Galvanized iron pipe plumbing can accumulate incoming lead and release it at a later time as particulates. The solubility of lead is governed by the formation of lead carbonates as pipe deposits. Wherever practicable, lead pipework should be replaced. Lead can also leach from lead-based solders and brass and bronze fittings.

The solubility of corrosion-related lead salts increases markedly as the pH increases above or decreases below 8.3 because of the substantial decrease in the equilibrium carbonate concentration. Thus, plumbosolvency tends to be at a maximum in waters with a low pH and low alkalinity, and a useful interim control procedure, pending pipe replacement, is to increase the pH to 8.0–8.5 after chlorination prior to distribution. Orthophosphate and other phosphates are effective in suppressing dissolution of lead.

Lead concentrations increase with increasing standing time of water in lead pipe. Flushing the pipework before drawing water for consumption can be used as an interim measure to reduce exposure to lead. Showering, bathing and flushing the toilet can be used to flush out the system.

Lead can corrode more rapidly when it is coupled to copper. The rate of such galvanic corrosion is faster than that of simple oxidative corrosion, and lead concentrations are not limited by the solubility of the corrosion products. The rate of galvanic corrosion is affected principally by chloride concentration. Galvanic corrosion is less easily controlled but can be reduced by dosing zinc in conjunction with orthophosphate and by adjustment of pH.

Treatment to reduce plumbosolvency usually involves pH adjustment. When the water is very soft (calcium carbonate concentration less than 50 mg/l), the optimum pH is about 8.0–8.5. Alternatively, dosing with orthophosphoric acid or sodium orthophosphate might be more effective, particularly when plumbosolvency occurs in non-acidic waters. Calcium carbonate precipitation indices such as Langelier and Ryznar are not considered to be necessarily good predictors of corrosion for lead.

A5.3.6 Nickel

Nickel in water may arise due to leaching from nickel- or chromium-plated taps as well as from stainless steel pipes and fittings. Nickel leaching is particularly influenced

by stagnation time. There is some evidence that corrosion control measures (e.g. pH control) may reduce leaching of nickel from stainless steel materials. Product certification is the most important means of control. Consumers, particularly nickel-sensitive people, should flush nickel- or chromium-plated taps before using the water, particularly after periods of stagnation.

A5.3.7 Zinc

Galvanized pipes will release zinc (from the galvanizing layer) and can also leach cadmium and lead. Corrosion can be a particular problem where galvanized steel or iron piping is connected to dissimilar materials, such as brass, in taps and fittings.

The solubility of zinc in water is a function of pH and total inorganic carbon concentrations; the solubility of basic zinc carbonate decreases with increase in pH and concentrations of carbonate species. For low-alkalinity waters, an increase of pH to 8.5 should be sufficient to control the dissolution of zinc.

With galvanized iron, the zinc layer initially protects the steel by corroding preferentially. In the long term, a protective deposit of basic zinc carbonate forms; however, galvanized pipe is also prone to uncontrolled deposition and clogging. Recent findings have shown that lead can accumulate on galvanized pipe particulates and become resuspended by physical disruption, such as water hammer. Protective deposits do not form in soft waters where the alkalinity is less than 50 mg/l as calcium carbonate or waters containing high carbon dioxide concentrations (> 25 mg/l), and galvanized steel is unsuitable for these waters. Electrolytic corrosion can occur where galvanized steel or iron pipes or fittings are connected with copper tube or brass fittings.