4. Radiological aspects

4.1 Introduction

The guideline levels for radioactivity in drinking-water recommended in the first edition of *Guidelines for drinking-water quality* in 1984 were based on the data available at that time on the risks of exposure to radiation sources. Since then, additional information has become available on the health consequences of exposure to radiation, risk estimates have been reviewed, and the recommendations of the International Commission on Radiological Protection (ICRP) have been revised. This new information has been taken into account in the preparation of the recommendations in this chapter.

The purpose of these recommendations for radioactive substances in drinking-water is to guide the competent authorities in determining whether the water is of an appropriate quality for human consumption.

4.1.1 Environmental radiation exposure

Environmental radiation originates from a number of naturally occurring and man-made sources. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has estimated that exposure to natural sources contributes more than 98% of the radiation dose to the population (excluding medical exposure). There is only a very small contribution from nuclear power production and nuclear weapons testing. The global average human exposure from natural sources is 2.4 mSv/year. There are large local variations in this exposure depending on a number of factors, such as height above sea level, the amount and type of radionuclides in the soil, and the amount taken into the body in air, food, and water. The contribution of drinking-water to the total exposure is very small and is due largely to naturally occurring radionuclides in the uranium and thorium decay series.

Levels of natural radionuclides in drinking-water may be increased by a number of human activities. Radionuclides from the nuclear fuel cycle and from medical and other uses of radioactive materials may enter drinking-water supplies; the contributions from these sources are normally limited by regulatory control of the source or practice, and it is through this regulatory mechanism that remedial action should be taken in the event that such sources cause concern by contaminating drinking-water.

4.1.2 Potential health consequences of radiation exposure

Exposure to ionizing radiation, whether natural or man-made, can cause two kinds of health effects. Effects for which the severity of the damage caused is proportional to the dose, and for which a threshold exists below which the effect does not occur, are called “deterministic” effects. Under normal conditions, the dose received from natural radioactivity and routine exposures from regulated practices is well below the threshold levels, and therefore deterministic effects are not relevant to these recommendations.

Effects for which the probability of occurrence is proportional to dose are known as “stochastic” effects, and it is assumed that there is no threshold below which they do not occur. The main stochastic effect of concern is cancer.

Because different types of radiation have different biological effectiveness and different organs and tissues in the body have different sensitivities to radiation, the ICRP has introduced radiation and tissue-weighting factors to provide a measure of equal effect. The sum of the doubly weighted dose received by all the tissues and organs of the body gives a measure of the total harm and is referred to as the effective dose. Moreover, radionuclides taken into the body may persist, and, in some cases, the resulting exposure may extend over many months or years. The committed effective dose is a measure of the total effective dose incurred over a lifetime following the intake of a radionuclide. It is this measure of exposure that is relevant to the present discussion; in what follows, the term “dose” refers to the committed effective dose, which is expressed in sieverts (Sv). The risk of adverse health consequences from radiation exposure is a function of the total dose received from all sources. A revised estimate of the risk (i.e., the mathematical expectation) of a lifetime fatal cancer for the general population has been estimated by the ICRP to be 5×10^{-2} per sievert. (This does not include a small additional health risk from non-fatal cancers or hereditary effects.)

4.1.3 Recommendations

- The recommended reference level of committed effective dose is 0.1 mSv from 1 year's consumption of drinking-water. This reference level of dose represents less than 5% of the average effective dose attributable annually to natural background radiation.

- Below this reference level of dose, the drinking-water is acceptable for human consumption, and any action to reduce the radioactivity is not necessary.

- For practical purposes, the recommended guideline activity concentrations are 0.1 Bq/litre for gross alpha and 1 Bq/litre for gross beta activity.

The recommendations apply to routine operational conditions of existing or new water supplies. They do not apply to a water supply contaminated during an emergency involving the release of radionuclides into the environment. Guidelines covering emergencies are available elsewhere (see Bibliography).

The recommendations do not differentiate between natural and man-made radionuclides.

4.2 Application of the reference level of dose

For practical purposes, the reference level of dose needs to be expressed as an activity concentration of radionuclides in drinking-water.

The dose to a human from radioactivity in drinking-water is dependent not only on intake but also on metabolic and dosimetric considerations. The guideline activity concentrations assume an intake of total radioactive material from the consumption of 2 litres of water per day for 1 year and are calculated on the basis of the metabolism of an adult. The influence of age on metabolism and variations in consumption of drinking-water do not require modification of the guideline activity concentrations, which are based on a lifetime exposure and provide an appropriate margin of safety. Metabolic and dosimetric considerations have been included in the development of dose conversion factors, expressed as sieverts per becquerel, which relate a dose expressed in sieverts to the quantity (in becquerels) of radioactive material ingested.

Examples of radionuclide concentrations (reference concentrations) corresponding to the reference level of dose, 0.1 mSv/year, are given in Table 8. These concentrations have been calculated using the dose conversion factors of the United Kingdom National Radiological Protection Board from the formula:

reference concentration (Bq/litre)

$$= \frac{1 \times 10^{-4}\ (\text{Sv}/\text{year})}{730\,(\text{litre}/\text{year}) \times \text{dose conversion factor}\ (\text{Sv}/\text{Bq})}$$

$$= \frac{1.4 \times 10^{-7}\ (\text{Sv}/\text{litre})}{\text{dose conversion factor}\ (\text{Sv}/\text{Bq})}$$

The previous guidelines recommended the use of an average gross alpha and gross beta activity concentration for routine screening. These were set at 0.1 Bq/litre and 1 Bq/litre, respectively. The doses associated with these levels of gross alpha and gross beta activity for selected radionuclides are shown in Table 9. For some radionuclides, such as ^{226}Ra and ^{90}Sr, the associated dose is much lower than 0.1 mSv per year. It can also be seen from this table that, if certain radionuclides, such as ^{232}Th, ^{228}Ra, or ^{210}Pb, are singly responsible for 0.1 Bq/litre for gross alpha activity or 1 Bq/litre for gross beta activity, then the reference level of dose of 0.1 mSv per year would be exceeded. However, these radionuclides usually represent only a small fraction of the gross activity. In addition, an elevated activity concentration of these radionuclides would normally be associated with high activities from other radionuclides. This would elevate the gross alpha or gross beta activity concentration above the investigation level and provoke specific radionuclide analysis. Therefore, the values of 0.1 Bq/litre for gross alpha activity and 1 Bq/litre for gross beta activity continue to be recommended as screening levels for drinking-water, below which no further action is required.

Table 8. Activity concentration of various radionuclides in drinking-water corresponding to a dose of 0.1 mSv from 1 year's intake

Radionuclide[a]	**Dose conversion factor (Sv/Bq)**[b]	**Calculated rounded value (Bq/litre)**
^{3}H	1.8×10^{-11}	7800
^{14}C	5.6×10^{-10}	250
^{60}Co	7.2×10^{-9}	20
^{89}Sr	3.8×10^{-9}	37
^{90}Sr	2.8×10^{-8}	5
^{129}I	1.1×10^{-7}	1
^{131}I	2.2×10^{-8}	6
^{134}Cs	1.9×10^{-8}	7
^{137}Cs	1.3×10^{-8}	10
^{210}Pb	1.3×10^{-6}	0.1
^{210}Po	6.2×10^{-7}	0.2
^{224}Ra	8.0×10^{-8}	2
^{226}Ra	2.2×10^{-7}	1
^{228}Ra	2.7×10^{-7}	1
^{232}Th	1.8×10^{-6}	0.1
^{234}U	3.9×10^{-8}	4
^{238}U	3.6×10^{-8}	4
^{239}Pu	5.6×10^{-7}	0.3

[a] For ^{40}K, see section 4.2. For ^{222}Rn, see section 4.2.3.

[b] Values from National Radiological Protection Board, *Committed equivalent organ doses and committed effective doses from intakes of radionuclides.* Chilton, Didcot, 1991.

Radionuclides emitting low-energy beta particles, such as ^{3}H and ^{14}C, and some gaseous or volatile radionuclides, such as ^{222}Rn and ^{131}I, will not be detected by standard methods of measurement. The values for average gross alpha and beta activities do not include such radionuclides, so that if their presence is suspected, special sampling techniques and measurements should be used.

Table 9. Examples of the doses arising from 1 year's consumption of drinking-water containing any of the given alpha-emitting radionuclides at an activity concentration of 0.1 Bq/litre or of the given beta-emitting radionuclides at an activity concentration of 1 Bq/litre[a]

Radionuclide	Dose (mSv)
Alpha emitters (0.1 Bq/litre)	
^{210}Po	0.045
^{224}Ra	0.006
^{226}Ra	0.016
^{232}Th	0.130
^{234}U	0.003
^{238}U	0.003
^{239}Pu	0.04
Beta emitters (1 Bq/litre)	
^{60}Co	0.005
^{89}Sr	0.003
^{90}Sr	0.020
^{129}I	0.080
^{131}I	0.016
^{134}Cs	0.014
^{137}Cs	0.009
^{210}Pb	0.95
^{228}Ra	0.20

[a] Appropriate dose conversion factors taken from National Radiological Protection Board, *Committed equivalent organ doses and committed effective doses from intakes of radionuclides,* Chilton, Didcot, 1991.

It should not necessarily be assumed that the reference level of dose has been exceeded simply because the gross beta activity concentration approaches or exceeds 1 Bq/litre. This situation may well result from the presence of the naturally occurring radionuclide ^{40}K, which makes up about 0.01% of natural potassium. The absorption of the essential element potassium is under homoeostatic control and takes place mainly from ingested food. Thus, the contribution to dose from the ingestion of ^{40}K in drinking-water, with its relatively low dose conversion factor (5×10^{-9} Sv/Bq), will be much less than that of many other beta-emitting radionuclides. This situation will be clarified by the identification of the specific radionuclides in the sample.

4.2.1 Analytical methods

The International Organization for Standardization (ISO) has published standard methods for determining gross alpha and gross beta activity concentrations in water. Although the detection limits depend on the radionuclides present, the dissolved solids in the sample, and the counting conditions, the recommended levels for gross alpha and gross beta activity concentrations should be above the limits of detection. The ISO detection limit for gross alpha activity based on ^{239}Pu is 0.04 Bq/litre, while that for gross beta activity based on ^{137}Cs is between 0.04 and 0.1 Bq/litre.

For analyses of specific radionuclides in drinking-water, there are general compendium sources in addition to specific methods in the technical literature (see Bibliography).

4.2.2 Strategy for assessing drinking-water

If either the gross alpha activity concentration of 0.1 Bq/litre or the gross beta activity concentration of 1 Bq/litre is exceeded, then the specific radionuclides should be identified and their individual activity concentrations measured. From these data, a dose estimate for each radionuclide should be made and the sum of these doses determined. Where the following additive formula is satisfied, no further action is required:

$$\sum_{i} \frac{C_i}{RC_i} \leq 1$$

where C_i is the measured activity concentration of radionuclide i and RC_i is the reference activity concentration of radionuclide i that, at an intake of 2 litres per day for 1 year, will result in a committed effective dose of 0.1 mSv (see Table 8).

If alpha-emitting radionuclides with high dose conversion factors are suspected, this additive formula may also be invoked when the gross alpha and gross beta activity screening values of 0.1 Bq/litre and 1 Bq/litre are approached. Where the sum exceeds unity for a single sample, the reference level of dose of 0.1 mSv would be exceeded only if the exposure to the same measured concentrations were to continue for a full year. Hence, such a sample does not in itself imply that the water is unsuitable for consumption and should be regarded only as a level at which further investigation, including additional sampling, is needed.

The options available to the competent authority to reduce the dose should then be examined. Where remedial measures are contemplated, any strategy considered should first be justified (in the sense that it achieves a positive net benefit) and then optimized in accordance with the recommendations of ICRP in order to produce the maximum net benefit. The application of these recommendations is summarized in Fig. 1.

<<I>> p120.gif ***Fig. 1. Application of recommendations on radionuclides in drinking-water based on an annual reference level of dose of 0.1 mSv***

4.2.3 Radon

There are difficulties in applying the reference level of dose to derive activity concentrations of ^{222}Rn in drinking-water. These difficulties arise from the ease with which radon is released from water during handling and the importance of the inhalation pathway. Stirring and transferring water from one container to another will liberate dissolved radon. Water that has been left to stand will have reduced radon activity, and boiling will remove radon completely. As a result, it is important that the form of water consumed is taken into account in assessing the dose from ingestion. Moreover, the use of water supplies for other domestic uses will increase the levels of radon in the air, thus increasing the dose from inhalation. This dose depends markedly on the form of domestic usage and housing construction. The form of water intake, the domestic use of water, and the construction of houses vary widely throughout the world. It is therefore not possible to derive an activity concentration for radon in drinking-water that is universally applicable.

The global average dose from inhalation of radon from all sources is about 1 mSv/year, which is roughly half of the total natural radiation exposure. In comparison, the global dose from ingestion of radon in drinking-water is relatively low. In a local situation, however, the risk from inhalation and ingestion may be about equal. Because of this and because there may be other sources of radon gas entry to a house, ingestion cannot be considered in isolation from inhalation exposures.

All these factors should be assessed on a regional or national level by the appropriate authorities, in order to determine whether a reference level of dose of 0.1 mSv is appropriate for that region, and to determine an activity concentration that may be used to assess the suitability of the water supply. These judgements should be based not only on the ingestion and inhalation exposures resulting from the supply of water, but also on the inhalation doses from other radon sources in the home. In these circumstances, it would appear necessary to adopt an integrated approach and assess doses from all radon sources, especially to determine the optimum action to be undertaken where some sort of intervention is deemed necessary.

5. Acceptability aspects

5.1 Introduction

The most undesirable constituents of drinking-water are undoubtedly those that are capable of having a direct impact on public health and for which guideline values have been developed. The management of these substances is in the hands of organizations responsible for the provision of the supply, and it is up to these organizations to instil in their consumers the confidence that this task is being undertaken with responsibility and efficiency.

To a large extent, consumers have no means of judging the safety of their drinking-water themselves, but their attitude towards their water supply and their water suppliers will be affected to a considerable extent by the aspects of water quality that they are able to perceive with their own senses. It is natural, therefore, for consumers to regard with grave suspicion water that appears dirty or discoloured or that has an unpleasant taste or smell, even though these characteristics may not in themselves be of any direct consequence to health.

The provision of drinking-water that is not only safe but also pleasing in appearance, taste, and odour is a matter of high priority. The supply of water that is unsatisfactory in this respect will undermine the confidence of consumers, leading to complaints and possibly the use of water from less safe sources. It can also result in the use of bottled water, which is expensive, and home treatment devices, some of which can have adverse effects on water quality.

The acceptability of drinking-water to consumers can be influenced by many different constituents; most of the substances for which guideline values have been set, and which also affect the taste or odour of water, have been referred to already (see section 3.6). There are a number of other water constituents that are of no direct consequence to health at the concentrations at which they normally occur in water but which nevertheless may be objectionable to consumers for various reasons.

The concentration at which such constituents are offensive to consumers is dependent on individual and local factors, including the quality of the water to which the community is accustomed and a variety of social, economic, and cultural considerations. Under these circumstances, it is inappropriate to set guideline values specific to substances that affect the acceptability of water to consumers but which are not directly relevant to health.

In the following summary statements, reference is made to levels likely to give rise to complaints from consumers. These are not precise numbers, and problems may occur at lower or much higher levels, depending on individual and local circumstances.

5.2 Summary statements

5.2.1 Physical parameters

Colour The colour of drinking-water is usually due to the presence of coloured organic matter (primarily humic and fulvic acids) associated with the humus fraction of soil. Colour is strongly influenced by the presence of iron and other metals, either as natural impurities or as corrosion products. It may also result from the contamination of the water source with industrial effluents and may be the first indication of a hazardous situation. The source of colour in a water supply should be investigated, particularly if a substantial change takes place.

Colours above 15 TCU (true colour units) can be detected in a glass of water by most people. Colours below 15 TCU are usually acceptable to consumers, but acceptability may vary according to local circumstances.

No health-based guideline value is proposed for colour in drinking-water.

Taste and odour

Taste and odour originate from natural and biological sources or processes (e.g., aquatic microorganisms), from contamination by chemicals, or as a by-product of water treatment (e.g., chlorination). Taste and odour may also develop during storage and distribution.

Taste and odour in drinking-water may be indicative of some form of pollution or of malfunction during water treatment or distribution. The cause of tastes and odours should be investigated and the appropriate health authorities should be consulted, particularly if there is a sudden or substantial change. An unusual taste or odour might be an indication of the presence of potentially harmful substances.

The taste and odour of drinking-water should not be offensive to the consumer. However, there is an enormous variation in the level and quality of taste and odour that are regarded as acceptable.

No health-based guideline value is proposed for taste and odour.

Temperature

Cool water is generally more palatable than warm water. High water temperature enhances the growth of microorganisms and may increase taste, odour, colour, and corrosion problems.

Turbidity

Turbidity in drinking-water is caused by particulate matter that may be present as a consequence of inadequate treatment or from resuspension of sediment in the distribution system. It may also be due to the presence of inorganic particulate matter in some ground waters.

High levels of turbidity can protect microorganisms from the effects of disinfection and can stimulate bacterial growth. In all cases where water is disinfected, therefore, the turbidity must be low so that disinfection can be effective. The impact of turbidity on disinfection efficiency is discussed in more detail in Chapter 6.

The appearance of water with a turbidity of less than 5 nephelometric turbidity units is usually acceptable to consumers, although this may vary with local circumstances. However, because of its microbiological effects, it is recommended that turbidity be kept as low as possible. No health-based guideline value for turbidity has been proposed.

5.2.2 Inorganic constituents

Aluminium

The presence of aluminium at concentrations in excess of 0.2 mg/litre often leads to consumer complaints as a result of deposition of aluminium hydroxide floe in distribution systems and the exacerbation of discoloration of water by iron; concentrations between 0.1 and 0.2 mg/litre may give rise to these problems in some circumstances.

Available evidence does not support the derivation of a health-based guideline value for aluminium in drinking-water.

Ammonia

The threshold odour concentration of ammonia at alkaline pH is approximately 1.5 mg/litre, and a taste threshold of 35 mg/litre has been proposed for the ammonium cation.

Ammonia is not of immediate health relevance, and no health-based guideline value has been proposed.

Chloride

High concentrations of chloride give an undesirable taste to water and beverages. Taste thresholds for the chloride anion depend on the associated cation and are in the range of 200-300 mg/litre for sodium, potassium, and calcium chloride. Consumers can become accustomed to concentrations in excess of 250 mg/litre.

No health-based guideline value is proposed for chloride in drinking-water.

Copper

The presence of copper in a water supply may interfere with the intended domestic uses of the water. Copper in public water supplies increases the corrosion of galvanized iron and steel fittings. Staining of laundry and sanitary ware occurs at copper concentrations above 1 mg/litre. At levels above 5 mg/litre, it also imparts a colour and an undesirable bitter taste to water.

Although copper can give rise to taste problems, the taste should be acceptable at the health-based provisional guideline value.

Hardness

Public acceptability of the degree of hardness of water may vary considerably from one community to another, depending on local conditions. The taste threshold for the calcium ion is in the range 100-300 mg/litre, depending on the associated anion, and the taste threshold for magnesium is probably less than that for calcium. In some instances, a water hardness in excess of 500 mg/litre is tolerated by consumers.

Depending on the interaction of other factors, such as pH and alkalinity, water with a hardness above approximately 200 mg/litre may cause scale deposition in the distribution system and will result in excessive soap consumption and subsequent “scum” formation. On heating, hard waters form deposits of calcium carbonate scale. Soft water, with a hardness of less than 100 mg/litre, may, on the other hand, have a low buffer capacity and so be more corrosive for water pipes (see section 6.6).

No health-based guideline value has been proposed for hardness.

Hydrogen sulfide

The taste and odour thresholds of hydrogen sulfide in water are estimated to be between 0.05 and 0.1 mg/litre. The “rotten eggs” odour of hydrogen sulfide is particularly noticeable in some ground waters and in stagnant drinking-water in the distribution system, as a result of oxygen depletion and the subsequent reduction of sulfate by bacterial activity.

Sulfide is oxidized rapidly to sulfate in well-aerated water, and hydrogen sulfide levels in oxygenated water supplies are normally very low. The presence of hydrogen sulfide in drinking-water can be easily detected by the consumer and requires immediate corrective action. It is unlikely that a person could consume a harmful dose of hydrogen sulfide from drinking-water, and hence a health-based guideline value has not been derived for this compound.

Iron

Anaerobic ground water may contain ferrous iron at concentrations of up to several milligrams per litre without discoloration or turbidity in the water when directly pumped from a well. On exposure to the atmosphere, however, the ferrous iron oxidizes to ferric iron, giving an objectionable reddish-brown colour to the water.

Iron also promotes the growth of “iron bacteria”, which derive their energy from the oxidation of ferrous iron to ferric iron and in the process deposit a slimy coating on the piping.

At levels above 0.3 mg/litre, iron stains laundry and plumbing fixtures. There is usually no noticeable taste at iron concentrations below 0.3 mg/litre, although turbidity and colour may develop. Iron concentrations of 1-3 mg/litre can be acceptable for people drinking anaerobic well-water.

No health-based guideline value is proposed for iron.

Manganese

Although manganese concentrations below 0.1 mg/litre are usually acceptable to consumers, this may vary with local circumstances. At levels exceeding 0.1 mg/litre, manganese in water supplies stains sanitary ware and laundry and causes an undesirable taste in beverages. The presence of manganese in drinking-water, like that of iron, may lead to the accumulation of deposits in the distribution system. Even at a concentration of 0.02 mg/litre, manganese will often form a coating on pipes, which may slough off as a black precipitate. In addition, certain nuisance organisms concentrate manganese and give rise to taste, odour, and turbidity problems in distributed water.

Although concentrations below 0.1 mg/litre are usually acceptable to consumers, this may vary with local circumstances. The provisional health-based guideline value for manganese is 5 times higher than this acceptability threshold of 0.1 mg/litre.

Dissolved oxygen

The dissolved oxygen content of water is influenced by the raw water temperature, composition, treatment, and any chemical or biological processes taking place in the distribution system. Depletion of dissoved oxygen in water supplies can encourage the microbial reduction of nitrate to nitrite and sulfate to sulfide, giving rise to odour problems. It can also cause an increase in the concentration of ferrous iron in solution.

No health-based guideline value has been recommended for dissolved oxygen.

pH

Although pH usually has no direct impact on consumers, it is one of the most important operational water quality parameters. Careful attention to pH control is necessary at all stages of water treatment to ensure satisfactory water clarification and disinfection. For effective disinfection with chlorine, the pH should preferably be less than 8. The pH of the water entering the distribution system must be controlled to minimize the corrosion of water mains and pipes in household water systems (see section 6.6). Failure to do so can result in the contamination of drinking-water and in adverse effects on its taste, odour, and appearance.

The optimum pH required will vary in different supplies according to the composition of the water and the nature of the construction materials used in the distribution system, but it is often in the range 6.5-9.5. Extreme values of pH can result from accidental spills, treatment breakdowns, and insufficiently cured cement mortar pipe linings.

No health-based guideline value has been proposed for pH.

Sodium

The taste threshold concentration of sodium in water depends on the associated anion and the temperature of the solution. At room temperature, the average taste threshold for sodium is about 200 mg/litre.

As no firm conclusions can be drawn regarding the health effects of sodium, no health-based guideline value has been derived.

Sulfate

The presence of sulfate in drinking-water can cause noticeable taste. Taste impairment varies with the nature of the associated cation; taste thresholds have been found to range from 250 mg/litre for sodium sulfate to 1000 mg/litre for calcium sulfate. It is generally considered that taste impairment is minimal at levels below 250 mg/litre.

It has also been found that addition of calcium and magnesium sulfate (but not sodium sulfate) to distilled water improves the taste; optimal taste was recorded at 270 and 90 mg/litre for the two compounds, respectively.

As sulfate is one of the least toxic anions, no health-based guideline value has been derived.

Total dissolved solids

Total dissolved solids (TDS) can have an important effect on the taste of drinking-water. The palatability of water with a TDS level of less than 600 mg/litre is generally considered to be good; drinking-water becomes increasingly unpalatable at TDS levels greater than 1200 mg/litre. Water with extremely low concentrations of TDS may be unacceptable because of its flat, insipid taste.

The presence of high levels of TDS may also be objectionable to consumers owing to excessive scaling in water pipes, heaters, boilers, and household appliances. Water with concentrations of TDS below 1000 mg/litre is usually acceptable to consumers, although acceptability may vary according to local circumstances.

No health-based guideline value for TDS has been proposed.

Zinc

Zinc imparts an undesirable astringent taste to water. Tests indicate a taste threshold concentration of 4 mg/litre (as zinc sulfate). Water containing zinc at concentrations in excess of 5 mg/litre may appear opalescent and develop a greasy film on boiling, although these effects may also be noticeable at concentrations as low as 3 mg/litre. Although drinking-water seldom contains zinc at concentrations above 0.1 mg/litre, levels in tapwater can be considerably higher because of the zinc used in plumbing materials.

No health-based guideline value has been proposed for zinc in drinking-water.

5.2.3 Organic constituents

Toluene

Toluene has a sweet, pungent, benzene-like odour. The reported taste threshold ranges from 40 to 120 µg/litre. The reported odour threshold for toluene in water ranges from 24 to 170 µg/litre. Toluene may therefore affect the acceptability of water at concentrations below its health-based guideline value.

Xylenes

Xylene concentrations in the range 300-1000 µg/litre produce a detectable taste and odour. The odour threshold for xylene isomers in water has been reported to range from 20 to 1800 µg/litre. The lowest odour threshold is lower than the health-based guideline value derived for the compound.

Ethylbenzene

Ethylbenzene has an aromatic odour. The reported odour threshold for ethyl-benzene in water ranges from 2 to 130 µg/litre. The lowest reported odour threshold is 100-fold lower than the health-based guideline value. The taste threshold ranges from 72 to 200 µg/litre.

Styrene

The average taste threshold reported for styrene in water at 40 °C is 120 µg/litre. Styrene has a sweet odour, and reported odour thresholds for styrene in water range from 4 to 2600 µg/litre, depending on temperature. Styrene may therefore be detected in water at concentrations below its health-based guideline value.

Monochlorobenzene

Taste and odour thresholds of 10-20 µg/litre and odour thresholds ranging from 40 to 120 µg/litre have been reported for monochlorobenzene. The health-based guideline value derived for monochlorobenzene far exceeds the lowest reported taste and odour threshold in water.

Dichlorobenzenes

Odour thresholds of 2-10 and 0.3-30 µg/litre have been reported for 1,2- and 1,4-dichlorobenzene, respectively. Taste thresholds of 1 and 6 µg/litre have been reported for 1,2- and 1,4-dichlorobenzene, respectively. The health-based guideline values derived for 1,2- and 1,4-dichlorobenzene far exceed the lowest reported taste and odour thresholds for these compounds.

Trichlorobenzenes

Odour thresholds of 10, 5-30, and 50 µg/litre have been reported for 1,2,3-, 1,2,4-, and 1,3,5-trichlorobenzene, respectively. A taste and odour threshold concentration of 30 µg/litre has been reported for 1,2,4-trichlorobenzene. The health-based guideline value derived for total trichlorobenzenes exceeds the lowest reported odour threshold in water of 5 µg/litre.

Synthetic detergents

In many countries, the earlier, persistent types of anionic detergent have been replaced by others that are more easily biodegraded, and hence the levels found in water sources have decreased substantially. New types of cationic, anionic, and non-ionic detergent have also been introduced. The concentration of detergents in drinking-water should not be allowed to reach levels giving rise to either foaming or taste or odour problems.

5.2.4 Disinfectants and disinfectant by-products

Chlorine

The taste and odour thresholds for chlorine in distilled water are 5 and 2 mg/litre, respectively. Most individuals are able to taste chlorine or its by-products (e.g., chloramines) at concentrations below 5 mg/litre, and some at levels as low as 0.3 mg/litre, although a residual chlorine concentration of between 0.6 and 1.0 mg/litre will generally begin to cause problems with acceptability. The taste threshold of 5 mg/litre is at the health-based guideline concentration.

Chlorophenols

Chlorophenols generally have very low organoleptic thresholds. The taste thresholds in water for 2-chlorophenol, 2,4-dichlorophenol, and 2,4,6-trichlorophenol are 0.1, 0.3 and 2 µg/litre, respectively. Odour thresholds are 10, 40, and 300 µg/litre, respectively. If water containing 2,4,6-trichlorophenol is free from taste, it is unlikely to present undue risk to health.

6. Protection and improvement of water quality

6.1 General considerations

Compliance with drinking-water quality standards, based on these guidelines, should provide assurance that the supply is safe. However, it must be recognized that adequate monitoring is essential to ensure continuing compliance, and that there are many potential situations - some of which can arise very quickly - that could cause potentially hazardous situations to develop.

Many potential problems can be prevented by safeguarding the integrity of the raw water source and its watershed, by proper maintenance and inspection of the treatment plant and distribution system, by the training of managers and plant personnel, and by consumer education. However, although it is essential that water suppliers periodically reassess their operations to ensure that conditions that could affect the quality of water have not changed, that periodic maintenance is performed, that repairs and renewals of equipment are undertaken without delay when required, that personnel are adequately trained, and that job skills are maintained, a discussion of these important facets of water supply is outside the scope of this publication. The reader is referred to the many excellent texts available on these topics for guidance (see Bibliography).

Where piped water of high quality is continuously available to household connections, monitoring of the quality of this water provides an indication of the risk of waterborne diseases. Nevertheless, these conditions of water supply are, globally, the exception rather than the rule, and many people collect water from sources away from the point of use or store water in insanitary conditions in the household. Similarly, even with adequate conditions of supply, household storage tanks and domestic plumbing may be sources of contamination if not properly installed and maintained. For these reasons, water is subject to contamination in the household, and this may often be the most important source of microbiological contamination. Where household storage occurs, the surveillance agency should investigate the risk that this represents to human health, and remedial actions, such as education regarding water handling and promotion of maintenance of household storage tanks, should be instigated. This subject is considered further in Volume 3 of *Guidelines for drinking-water quality.*

It should be emphasized that, in terms of water quality, pathogenic microorganisms remain the most important danger to drinking-water in both developed and developing countries.

6.2 Selection and protection of water sources

Proper selection and protection of water sources are of prime importance in the provision of safe drinking-water. It is always better to protect water from contamination than to treat it after it has been contaminated.

Before a new source of drinking-water supply is selected, it is important to ensure that the quality of the water is satisfactory or treatable for drinking and that the quantity available is sufficient to meet continuing water demands, taking into account daily and seasonal variations and projected growth in the size of the community being served.

The watershed should be protected from human activities. This could include isolation of the watershed and/or control of polluting activities in the area, such as dumping of hazardous wastes, mining and quarrying, agricultural use of fertilizers and pesticides, and the limitation and regulation of recreational activities.

Sources of ground water such as springs and wells should be sited and constructed so as to be protected from surface drainage and flooding. Zones of ground water abstraction should be fenced to prevent public access, kept clean of rubbish, and sloped to prevent the collection of pools in wet weather. Animal husbandry should be controlled in such zones.

Protection of open surface water is a problem. It may be possible to protect a reservoir from major human activity, but, in the case of a river, protection may be possible only over a limited reach, if at all. Often it is necessary to accept existing and historical uses of a river or lake and to design the treatment accordingly.

6.3 Treatment processes

Water treatment processes used in any specific instance must take into account the quality and nature of the water supply source. The intensity of treatment must depend on the degree of contamination of the source water. For contaminated water sources, multiple treatment barriers to the spread of pathogenic organisms are particularly important and should be used to give a high degree of protection and to reduce the reliance on any individual treatment step.

The fundamental purpose of water treatment is to protect the consumer from pathogens and impurities in the water that may be offensive or injurious to human health. Urban treatment of water from lowland sources usually consists of (1) reservoir storage or pre-disinfection, (2) coagulation, flocculation, and sedimentation (or flotation), (3) filtration, and (4) disinfection. Alternative or additional processes may be interposed to meet local conditions. Disinfection is the final safeguard and also protects drinking-water during distribution against external contamination and regrowth. The whole treatment sequence may indeed be regarded as conditioning the water for effective and reliable disinfection. Urban water treatment is, in effect, a four-stage multiple-barrier system for the removal of microbial contamination.

The multiple-barrier concept can be adapted for treating surface waters in rural and remote regions. A typical series of processes would include (1) storage, (2) sedimentation or screening, (3) gravel pre-filtration and slow-sand filtration, and (4) disinfection. Such treatment is considered in detail in Volume 3.

6.3.1 Pre-treatment

Surface waters may be either stored in reservoirs or disinfected before treatment.

During impoundment of water in lakes or reservoirs, the microbiological quality improves considerably as a result of sedimentation, the lethal effect of the ultraviolet content of sunlight in surface layers of water, and starvation and predation. Reductions of faecal indicator bacteria, salmonella, and enteroviruses are about 99%, being greatest during the summer and with residence periods of the order of 3-4 weeks.

Pre-disinfection is usual when water is abstracted and treated without storage. It will destroy animal life and reduce numbers of faecal bacteria and pathogens, besides assisting in the removal of algae during coagulation and filtration. An additional important function is the removal of ammonia. A drawback is that, when chlorine is used to excess, chlorinated organic compounds and biodegradable organic carbon will be produced.

Microstraining through very fine screens, typically with an average pore diameter of 30 µm, is an effective way of removing many microalgae and zooplankton that may otherwise clog or even penetrate filters. It has little, if any, effect in reducing numbers of faecal bacteria and enteric pathogens.

Where water of a very high quality is required, infiltration of raw or partly treated surface water into river banks or sand dunes can be practised, as notably in the Netherlands. Infiltration serves as a buffer in case raw river water cannot be used, because of incidents such as industrial pollution. The abstracted water usually needs additional treatment to remove iron or manganese compounds, and the detention period needs to be as long as possible to attain a quality approaching that of ground water. Removal of faecal bacteria and viruses exceeds 99%.

6.3.2 Coagulation, flocculation, and sedimentation

Coagulation involves the addition of chemicals (e.g., aluminium sulfate, ferrous or ferric sulfate, and ferric chloride) to neutralize the charges on particles and facilitate their agglomeration during the slow mixing provided in the flocculation step. Floes thus formed co-precipitate, absorb, and entrap natural colour and mineral particles and can bring about major reductions in turbidity and in counts of protozoa, bacteria and viruses.

Coagulation and flocculation require a high level of supervisory skill. Before it is decided to use coagulation as part of a treatment process, careful consideration must be given to the likelihood of a regular supply of chemicals and the availability of qualified personnel.

The purpose of sedimentation is to permit settleable floe to be deposited and thus reduce the concentration of suspended solids that must be removed by filters. Among the factors that influence sedimentation are: size, shape, and weight of the floe; viscosity and hence temperature of the water; detention time; number, depth, and areas of the basins; surface overflow rate; velocity of flow; and inlet and outlet design. Plans must be made for the collection and safe disposal of sludge from sedimentation tanks. Flotation is an alternative to sedimentation when the amount of floe is slight.

For the coagulation/sedimentation process to be most effective for the control of trihalomethanes, the initial point of chlorine application should be after the coagulation/sedimentation process, to allow for as much precursor removal as possible prior to chlorination. Reductions in trihalomethane production of up to 75% in full-scale plants have been reported as a result of moving the initial chlorination application point past the coagulation/sedimentation process.

6.3.3 Rapid and slow sand filtration

When rapid filtration follows coagulation, its performance in removing microorganisms and turbidity varies through the duration of the run between backwashings. Immediately after backwashing, performance is poor, until the bed has compacted. Performance will also deteriorate progressively at the stage when back-washing is needed, as floe may escape through the bed into the treated water. These features emphasize the need for proper supervision and control of filtration at the waterworks.

Slow sand filtration is simpler to operate than rapid filtration, as frequent backwashing is not required. It is therefore particularly suitable for developing countries and small rural systems, but it is applicable only if sufficient land is available.

When the slow sand filter is first brought into use, a microbial slime community develops on the sand grains, particularly at the surface of the bed. This consists of bacteria, free-living ciliated protozoa and amoebae, crustacea, and invertebrate larvae acting in food chains, resulting in the oxidation of organic substances in the water and of ammoniacal nitrogen to nitrate. Pathogenic bacteria, viruses, and resting stages of parasites are removed, principally by adsorption and by subsequent predation. When correctly loaded, slow sand filtration brings about the greatest improvement in water quality of any single conventional water treatment process. Bacterial removal will be 98-99.5% or more, *E. coli* will be reduced by a factor of 1000, and virus removal will be even greater. A slow sand filter is also very efficient in removing parasites (helminths and protozoa). Slow sand filters are somewhat more effective when the water is warm. Nevertheless, the effluent from a slow sand filter might well contain a few *E. coli* and viruses, especially during the early phase of a filter run and with low water temperatures.

6.3.4 Disinfection

Terminal disinfection of piped drinking-water supplies is of paramount importance and is almost universal, as it is the final barrier to the transmission of water-borne bacterial and viral diseases. Although chlorine and hypochlorite are most often used, water may also be disinfected with chloramines, chlorine dioxide, ozone, and ultraviolet irradiation.

The efficacy of any disinfection process depends upon the water being treated beforehand to a high degree of purity, as disinfectants will be neutralized to a greater or lesser extent by organic matter and readily oxidizable compounds in water. Microorganisms that are aggregated or are adsorbed to particulate matter will also be partly protected from disinfection and there are many instances of disinfection failing to destroy waterborne pathogens and faecal bacteria when the turbidity was greater than 5 nephelometric turbidity units (NTU). It is therefore essential that the treatment processes preceding terminal disinfection are always operated to produce water with a median turbidity not exceeding 1 NTU and not exceeding 5 NTU in any single sample. Values well below these levels will regularly be attained with a properly managed plant.

Normal conditions of chlorination (i.e., a free residual chlorine of $\geq$ 0.5 mg per litre, at least 30 minutes contact, pH less than 8.0, and water turbidity of less than 1 NTU) can bring about over 99% reductions of *E. coli* and certain viruses but not of the cysts or oocysts of parasitic protozoa.

The growth of bacteria within activated carbon point-of-use water filters has been well documented. Some manufacturers of carbon filters have attempted to avoid this problem by incorporating silver, as a bacteriostatic agent, in the filters. However, all of the published reports on this topic have convincingly demonstrated that this practice has a limited effect. It is believed that the presence of silver in these filters selectively permits the growth of silver-tolerant bacteria. For this reason, it is imperative that these devices be used only with drinking-water known to be microbiologically safe and that devices be well flushed prior to each use. Silver is occasionally used to disinfect drinking-water on board ships. However, because long contact times or high concentrations are essential, the use of silver for disinfection is not considered practical for point-of-use applications.

6.3.5 Fluoride removal

High fluoride levels, above 5 mg/litre, have been found in several countries (e.g., Algeria, China, Egypt, India, and Thailand). Such high levels have at times led to dental or skeletal fluorosis.

Fluoride removal techniques have been developed for both community water supplies and individual households. The most frequently employed fluoride removal technique uses ion exchange/adsorption with either charred bone-meal or activated alumina. Full-scale activated alumina facilities and household defluoridators using charred bone-meal have been reported to reduce fluoride levels from 5-8 mg/litre to less than 1 mg/litre. Fluoride-spent bone-meal and activated alumina are usually regenerated for further use.

6.4 Choice of treatment

In small communities in rural areas, protection of the source of water may be the only form of treatment possible. Such supplies are considered in detail in Volume 3. Where communities are large, the demand for water is high and can often be met only by using additional sources of poor microbiological quality. Such waters will require all the resources of water treatment to yield an attractive and safe drinking-water.

Ground waters extracted from deep, well-protected aquifers are usually free from pathogenic microorganisms, and the distribution of such untreated ground water is common practice in many countries. This practice implies that the area of influence is protected by effective regulatory measures and that the distribution system is adequately protected against secondary contamination of the drinking-water. If continuous protection from source to consumer cannot be guaranteed, then disinfection and the maintenance of adequate concentrations of residual chlorine are imperative.

Surface water will usually require full treatment. The degrees of removal of microorganisms by coagulation, flocculation, sedimentation, and rapid filtration are, with proper design and operation, equivalent to those for slow sand filtration.

Additional treatment, such as ozonation, followed by activated carbon treatment to remove assimilable organic carbon, reduces the potential for after growth problems caused by nuisance bacteria in distribution networks. The ozonation stage may also have a significant effect on reducing pathogens. Disinfection should be regarded as obligatory for all piped supplies using surface water, even those derived from high-quality, unpolluted sources, as there should always be more than one barrier against the transmission of infection in a water supply. In large, properly run waterworks, the criteria for the absence of *E. coli* and coliform bacteria can then be met with a very high degree of probability. The current trend is to optimize the use of chemicals such as chlorine and coagulants in water treatment, and to develop physical or biological methods of treatment, in order to reduce the doses of chemicals required, thereby reducing the formation of disinfection by-products.

6.5 Distribution networks

The distribution network transports water from the place of treatment to the consumer. Its design and size will be governed by the topography and the location and size of the community. The aim should always be to ensure that consumers receive a sufficient and uninterrupted supply, and that contamination is not introduced in transit.

Distribution systems are especially vulnerable to contamination when the pressure falls, particularly in the intermittent supplies of many cities in developing countries. Suction is often created by direct pumping from the mains to private storage tanks, a practice that should be minimized.

The bacteriological quality of water can deteriorate during distribution. If the water contains significant assimilable organic carbon or ammonia, adequate residual levels of disinfectant are not maintained. If such water-mains are not flushed and cleaned frequently enough, growth of nuisance bacteria and other organisms can occur. Where the water contains appreciable assimilable organic carbon (> 0.25 mg/litre) and where the water temperature exceeds 20 °C, a concentration of residual free chlorine of 0.25 mg/litre may be required to prevent growth of

Aeromonas and other nuisance bacteria. Attached microorganisms may grow even in the presence of residual chlorine. The aim should be to produce biologically stable water, with very low levels of organic compounds and ammonia to prevent problems from microbial growth in distribution.

Underground storage tanks and service reservoirs must be inspected for deterioration and for infiltration of surface and ground water. It is desirable for the land enclosing underground storage tanks to be fenced off to prevent access by humans and animals and to prevent damage to the structures.

Repair works to mains offer another possibility for contamination. Local loss of pressure may result in back-siphonage of contaminated water, unless check valves are introduced into the water system at sensitive points, such as supplies to garden irrigation and urinals. If the main has been damaged and if there is the possibility that wastewater from a fractured sewer or drain may have entered, the situation is most serious. The actions that must be taken to protect consumers from waterborne disease should be specified in national codes of practice and in local instructions to waterworks staff.

Microbial contamination can occur by growth on unsatisfactory construction materials coming into contact with water, such as washers, pipe lining compounds, and plastics used in pipes and taps. National systems should be in operation controlling the use of such materials.

6.6 Corrosion control

6.6.1 Introduction

Corrosion is characterized by the partial solubilization of the materials constituting the treatment and supply systems, tanks, pipes, valves, and pumps. It may lead to structural failure, leaks, loss of capacity, and deterioration of chemical and microbiological water quality. The internal corrosion of pipes and fittings can have a direct impact on the concentration of some water constituents for which guideline values have been recommended, including cadmium, copper, iron, lead, and zinc. Corrosion control is therefore an important aspect of the management of a water supply system.

Because of its implications for water quality, the present discussion will deal only with the internal corrosion of pipes; the protection of pipes against external corrosion is extremely important, but is much less relevant to water quality.

Corrosion control involves many parameters, including the concentrations of calcium, bicarbonate, carbonate, and dissolved oxygen, as well as pH. The detailed requirements differ for every water and for each distribution material.

6.6.2 Basic considerations

Many metals, including most of those used in the construction of water supply systems, are unstable in the presence of water and have a tendency to transform or degrade to a more stable and often soluble form - a process recognizable as corrosion. The rate at which this takes place is governed by many chemical and physical factors; it may be very rapid or extremely slow.

Of great importance are the properties of the products of corrosion, the stable end-products of the process. If any of these is soluble in water, then corrosion will tend to be rapid. In some cases, however, where the corrosion products are insoluble, a protective scale may be formed at the water surface, and corrosion then becomes very slow. Insoluble corrosion products are protective only where they form an impenetrable layer. If they form a spongy or flocculent mass, corrosion will continue, leading to a deterioration of water quality, a reduction of the carrying capacity of the pipe, and microbial growths (biofilms), which may be protected from residual chlorine.

Corrosion is also greatly influenced by the electrical properties of the metals in contact with water. Different metals show different tendencies to develop an electric charge in contact with water, and this difference is displayed in the so-called galvanic series. Where two different metals (or other electrically conducting materials) are in contact, a galvanic cell is formed in which metal will dissolve at the negative electrode. It is not necessary for the two metals involved to be at the same location provided that they are in electrical contact. The formation of galvanic cells often provides the driving force for corrosion.

The rate of corrosion is governed mainly by the rate at which dissolved reactants are transported to the metal surface and the rate at which dissolved products are transported away from the reaction site. Thus, corrosion rates increase directly with increasing concentration of ions in the water and also with increasing degrees of agitation.

At very high water velocities, the rate of corrosion may increase dramatically as a result of erosion corrosion. In common with other chemical reactions, corrosion rates increase with temperature.

Certain metals undergo a phenomenon known as passivation. For these metals, which include iron, nickel, and chromium, and their alloys, the application of a certain voltage results in a substantial decrease in corrosion rate, which is maintained over a considerable range of applied voltage. The process is exploited in some corrosion control strategies, including “anodic protection”. Copper, lead, and zinc corrosion cannot be controlled by anodic protection.

6.6.3 Effect of water composition

Dissolved oxygen is one of the most important factors influencing the rate of corrosion. It is a direct participant in the corrosion reaction, and, under most circumstances, the higher its concentration the higher the corrosion rate.

pH controls the solubility, rate of reaction, and, to some extent, the surface chemistry of most of the metal species involved in corrosion reactions. It is particularly important in relation to the formation of a protective film at the metal surface.

There is increasing evidence of the importance of the aggressive action of the chloride ion in the corrosion of metals used in distribution systems. There is some evidence that residual chlorine also affects the rate of corrosion.

6.6.4 Corrosion of pipe materials

Copper

Copper tubing may be subject to general corrosion, impingement attack, and pitting corrosion. General corrosion of copper is most often associated with soft, acidic waters; waters with a pH below 6.5 and a hardness of less than 60 mg/litre (as $CaCO_3$) are very aggressive to copper and should not be transported in copper pipes or heated in copper boilers. 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 ground waters having a carbon dioxide concentration above 5 mg/litre and a high dissolved oxygen level. Surface waters containing organic colour (humic substances) may also be associated with pitting corrosion. A high proportion of general and pitting corrosion problems are associated with new pipes in which a protective oxide layer has not yet formed.

Lead

The corrosion of lead (plumbosolvency) is of particular concern because of its adverse effect on water quality. Lead piping is still common in old houses, and lead solders have been used widely, particularly for jointing copper tube. Lead is stable in water in a number of forms, depending on pH, and the solubility of lead is governed to a large extent by the formation of insoluble lead carbonate. The solubility of lead increases markedly as the pH is reduced below 8 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 maintain pH in the range 8.0-8.5.

Cement and concrete

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 (A/C) pipes, the aggregate is asbestos fibres. Cement is subject to deterioration on prolonged exposure to aggressive water - due either to the dissolution of lime and other soluble compounds or to chemical attack by aggressive ions such as chloride or sulfate - and this may result in structural failure of the cement pipe. The aggressiveness of a water to cement is related to the value of the Langelier index, which measures the potential for precipitation or dissolution of calcium carbonate (see section 6.6.6). There is also a similar “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.

6.6.5 Microbiological aspects of corrosion

Microorganisms can play a significant role in the corrosion of pipe material by forming micro-zones of low pH or high concentrations of corrosive ions, mediating oxidation processes or the removal of corrosion products, and disrupting protective surface films. The most significant bacteria involved in corrosion are the sulfate-reducing and the iron bacteria, but nitrate reducers and methane producers may have a role in some situations. Corrosion induced by microorganisms tends to be a problem in distribution systems where a residual concentration of chlorine has not been maintained, especially in “dead ends” and other situations where the flow is low. It may also be a problem where there has been heavy scale deposition or where bulky corrosion products have formed.

6.6.6 Corrosion indices

A number of indices have been developed to characterize the corrosion potential of any particular water. Most are based on the assumption that water with a tendency to deposit a calcium carbonate scale on metal surfaces will be less corrosive. Thus, the well-known Langelier index is the difference between the actual pH of a water and its “saturation pH”, this being the pH at which a water of the same alkalinity and calcium hardness would be at equilibrium with solid calcium carbonate. In addition to the calcium hardness and alkalinity, the calculation of the saturation pH takes account of the concentration of the total dissolved solids and the temperature.

Waters with a pH higher than their saturation pH (positive Langelier index) are supersaturated with respect to calcium carbonate and will therefore tend to deposit a scale. Conversely, waters with a pH lower than their saturation pH (negative Langelier index) will be undersaturated with respect to calcium carbonate and are therefore considered to be aggressive. Nomographs are available to simplify the determination of the saturation pH. Ideally, distributed water should be at or slightly above its saturation pH.

The Langelier index and other indices based on similar principles have proved to be helpful in predicting and dealing with corrosion problems in many situations. Clearly, however, the assumption that a calcium carbonate scale will always be protective and that water that does not lay down such a scale will always be corrosive oversimplifies a complex phenomenon. It is not surprising, therefore, that attempts to quantify aggressiveness on this basis have produced mixed results. The ratio of the chloride and sulfate concentrations to the bicarbonate concentration (Larson ratio) has been shown to be helpful in assessing the corrosiveness of water to cast iron and steel. A similar approach has been used in studying dissolution of zinc from brass fittings.

6.6.7 Strategies for corrosion control

The main strategies for corrosion control include:

- the control of environmental parameters affecting corrosion rate,
- the addition of chemical inhibitors,
- electrochemical measures, and
- considerations of system design.

To control corrosion in water distribution networks, the methods most commonly applied are controlling pH, increasing the carbonate hardness, or adding corrosion inhibitors such as sodium polyphosphates or silicates and zinc orthophosphate. The quality and maximum dose to be used should be in line with appropriate national specifications for such water treatment chemicals. Although pH control is an important approach, its possible impact on other aspects of water supply technology, including disinfection, must always be taken into account.

6.7 Emergency measures

It is essential that water suppliers develop contingency plans to be invoked in the event of an emergency. These plans should consider potential natural disasters (such as earthquakes, floods, damage to electrical equipment by lightning strikes), accidents (spills in the watershed), damage to treatment plant and distribution system, and human actions (strikes, sabotage). Contingency plans should clearly specify responsibilities for coordinating measures to be taken, a communication plan to alert and inform users of the supply, and plans for providing and distributing emergency supplies of water.

In an emergency, a decision to close the supply carries an obligation to provide an alternative safe supply. Advising consumers to boil water, initiating super-chlorination, and undertaking immediate corrective measures may be preferable. National drinking-water standards are intended to ensure that the consumer enjoys safe potable water, not to shut down deficient water supplies.

During an emergency in which there is evidence of faecal contamination of the supply, it may be necessary either to modify the treatment of existing sources or temporarily to use alternative sources of water. It may be necessary to increase disinfection at source or to rechlorinate during distribution. If possible, the distribution system should be kept under continuous pressure, as failure in this respect will considerably increase the risks of entry of contamination to the pipework and thus the possibility of waterborne disease. If the quality cannot be maintained, consumers should be advised to boil the water during the emergency. The water should be brought to a vigorous rolling boil for 1 minute. As water boils at a lower temperature at high altitude, a minute of extra boiling time should be added for every 1000 m above sea-level. This should kill or inactivate the vegetative cells of bacteria and viruses as well as the cysts of *Giardia.* If bulk supplies in tankers are used, sufficient chlorine should be added to ensure that a free residual concentration of at least 0.5 mg/litre for a minimum of 30 minutes is present at the delivery point. Before use, tankers should be either disinfected or steam-cleaned. The temporary use of other disinfectant measures, such as slow-release disinfectant tablets added to water drawn from the tap, should also be considered if they have been proven to give safe and reliable disinfection.

It is impossible to give general guidance concerning emergencies in which chemicals cause massive contamination of the supply. The guideline values recommended relate to a level of exposure that is regarded as tolerable throughout life; acute toxic effects are not normally considered in the assessment of a TDI. The length of time during which exposure to a chemical far in excess of the guideline value would be toxicologically detrimental will depend upon factors that vary from contaminant to contaminant. The biological half-life of the contaminant, the nature of the toxicity, and the amount by which the exposure exceeds the guideline value are all crucial. In an emergency situation the public health authorities must be consulted about appropriate action.