# 1

# The microbiology of piped distribution systems and public health

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## 1.1 INTRODUCTION

This chapter discusses the microbiology of piped water distribution systems and its relationship to public health. Piped systems are generally buried complex reticulations; consequently, they are relatively difficult to operate and maintain. However, they are as important as water resource and treatment facilities in ensuring the supply of safe drinking-water.

A drinking-water distribution system provides a habitat for microorganisms, which are sustained by organic and inorganic nutrients present on the pipe and in the conveyed water. A primary concern is therefore to prevent contamination from faecal material that might build up near pipes or contaminate surface or

*Safe Piped Water: Managing Microbial Water Quality in Piped Distribution Systems*. Edited by Richard Ainsworth. ISBN: 1 84339 039 6. Published by IWA Publishing, London, UK.

soil water. Generally, bacteria present in the water and on surfaces are harmless, but they are at the base of a food-chain for other free-living organisms such as fungi, protozoa, worms and crustaceans. These organisms may be present in a distribution system, even in the presence of residual disinfectant, and the water can still be free of health risks. However, excessive microbial activity can lead to deterioration in aesthetic quality (e.g. tastes, odours and discolouration) and can interfere with the methods used to monitor parameters of health significance. Therefore, additional treatment may be needed to control the quality of the treated water in a distribution system, to prevent excessive microbial growth and any associated occurrence of larger life forms (AWWA, 1999). This subject is discussed in Chapter 2, which provides guidance on operating treatment processes to minimize problems in water distribution.

Maintaining good water quality in distribution will also depend on the operation and design of the distribution system (Chapter 3), and will require maintenance and survey procedures to prevent contamination, and to remove and prevent the accumulation of internal deposits (Chapter 4). Performing any work on the system that entails contact with conveyed water or internal surfaces increases the risk of contamination. Such situations require well-documented hygienic working practices, as discussed in Chapter 5. Chapters 3–5 summarize practices to maintain microbial quality. The practices are also relevant to the prevention of problems of discoloured water, odours and tastes. The provision of tap water that is both aesthetically pleasing and safe is important, because it will discourage the consumption of alternative supplies that may not be safe, even if they appear to be so.

The traditional approach to verifying the microbial safety of piped public water supplies has relied on sampling strategies based on the end-product — that is, tap water. Guidelines or regulations describing limits for microbial content have been set by government-enacted laws in many countries and the normal rationale for these is that historical data have shown compliant water to be safe. However, the effectiveness of some of these guidelines and regulations has been challenged by epidemiological studies. Analysis of data accumulated over the 20th century has suggested that some of the microbial standards (e.g. heterotrophic plate count, total coliforms and thermotolerant coliforms) have little predictive value for public health purposes in certain situations (WHO, 2003). Outbreaks have sometimes occurred when drinking-water met such standards (Sobsey, 1989; Craun, Berger & Calderon, 1997). This is either because some pathogens are more difficult to remove or have a higher level of resistance to disinfection processes than the indicator microorganisms stipulated in the standards, or because the sampling frequency is too low to reveal contamination, particularly when it is transient.

The identification and enumeration of microorganisms is slow, and hence is not suitable for early warning or control purposes. Sampling and monitoring the microbial quality of the water supplied to the consumer can only verify that the water was safe after it was supplied and perhaps ingested. In such situations a holistic approach to quality assurance is important and should include:

- assessment and control of source waters to prevent or reduce pathogen contamination;
- selection and operation of treatment processes to reduce pathogens to target levels;
- prevention of contamination by pathogens in the supply and distribution system.

These stages in the water supply process can be considered in the framework of a water safety plan and, where possible, the adoption of real-time controls to reduce pathogens to safe levels, from source to supply. This approach builds on the "hazard analysis and critical control point" (HACCP) system, which has gained the approval of the food industry for controlling food quality. Its application to controlling water quality in the context of a water safety plan is described in the third edition of the World Health Organization (WHO) *Guidelines for Drinking-water Quality* (WHO, 2004). Much of the information provided in this and subsequent chapters is appropriate for the development of the distribution section of such plans, and Chapter 7 provides guidance on the development of water safety plans for distribution systems.

The present chapter reviews the importance of distribution systems in supplying safe water, the fate of pathogens in such systems, and the relevance of monitoring microbiological parameters in distribution and at the point of supply for assuring water quality.

## 1.2 WATERBORNE DISEASE DUE TO CONTAMINATION OF THE DISTRIBUTION SYSTEM

Data from countries that have a surveillance system for waterborne diseases have provided numerous examples of the importance of a secure and well-operated distribution system in supplying safe drinking-water.

In the United States of America (USA), from 1920 to 1990, 11–18% of reported outbreaks of waterborne disease were attributable to contamination of the distribution system. From 1991 to 1996, contamination of water in the distribution system was responsible for 22% of the reported outbreaks, caused by corrosion, cross-connections, backflow, improperly protected storage or repairs to water mains and plumbing (Craun and Calderon, 1999; Craun, 1986).

In the United Kingdom, from 1911 to 1995, problems related to the distribution system accounted for 15 (36%) of 42 reported waterborne disease outbreaks in public water supplies (Hunter, 1997). Similarly, in Scandinavia, between 1975 and 1991, cross-connections or backflow were responsible for

20% of the reported waterborne disease outbreaks in community supplies and 37% of the outbreaks in private systems (Stenström, 1994).

Deteriorating water treatment facilities and distribution systems can pose a significant public health threat, as illustrated by a study in Uzbekistan (Semenza et al., 1998). More than 30% of the households with piped water lacked detectable levels of chlorine residuals in their drinking-water, despite two-stage chlorination of the source water, and were at increased risk of diarrhoea. Forty-two percent of these municipal users reported that water pressure had been intermittent within the previous two days. There was a dramatic reduction in diarrhoeal rates when home chlorination was implemented, indicating that a large proportion of diarrhoeal disease was waterborne. The authors concluded that the epidemiological data supported the hypothesis that diarrhoeal disease could be attributed to cross-contamination between the municipal water supply and sewer, due to leaky pipes and lack of water pressure.

An epidemic of cholera that began in Peru in January 1991 marked the first such epidemic in South America since the 19th century. Subsequently, over 533 000 cases and 4700 deaths have been reported from 19 countries in that continent. In Trujillo, the second largest city in Peru, the water supply was unchlorinated and water contamination was common (Swerdlow et al., 1992a; Besser et al., 1995). A water-quality study showed progressive contamination during distribution and storage in the home. Illegal cross-connections, low and intermittent water pressure and the lack of chlorination all contributed to the widespread contamination. These authors found a wide variability in chlorine concentrations in the municipal water that was distributed to dwellings. *Vibrio cholerae* was isolated from water samples. Trujillo's water and sanitation problems, which are found on all continents, reinforce the need for measures to prevent the spread of epidemic waterborne diseases at the treatment plant, in the distribution system and at the household level.

It is not only developing countries that are at risk, as illustrated by a large *Escherichia coli* O157:H7 outbreak in a small rural township in Missouri, in the USA, that had an unchlorinated water supply (Swerdlow et al., 1992b). There were 243 case patients, of whom 86 had bloody stools, 32 were hospitalised, 4 died and 2 had haemolytic uremic syndrome. In a case–control study, no food was associated with illness, but ill persons had drunk more municipal water than had the controls (Swerdlow et al., 1992b). The study showed that, during the peak of the outbreak, bloody diarrhoea was 18.2 times more likely to occur in persons living inside the city and using municipal water than in persons living outside the city and using private well water. Shortly before the peak of the outbreak, 45 water meters were replaced and two water mains ruptured. The number of new cases declined rapidly after residents were ordered to boil water and the water supply was chlorinated. This was one of the largest outbreaks of *E. coli* O157:H7 infection and the first that was shown to be transmitted by water. System-wide chlorination, as well as hyperchlorination during repairs, might have prevented the outbreak.

## 1.3 MICROORGANISMS IN THE DISTRIBUTION SYSTEM

### 1.3.1 Microorganisms entering distribution systems by surviving the treatment processes

The first barrier required to prevent microorganisms from entering drinking-water is protection of the water source. Effective water source protection, including the construction of headworks and the control of land use within the catchment or recharge area, will greatly reduce the numbers of pathogenic microorganisms in source water. This in turn reduces reliance on treatment processes to ensure water of acceptable quality. In many situations where groundwater is used, source protection measures can be designed to largely prevent contamination by pathogens.

Source protection is particularly important when dealing with small, community-managed water supplies. In many cases, community-managed distribution systems do not apply any form of treatment. Prevention of microbial entry at the start of the distribution system therefore relies on well-maintained source protection measures. Failures in source protection are likely to result in contamination of the water supply

Catchment protection has also been shown to be important in the control of pathogens in drinking-water supplies using treated surface waters (Hellard et al., 2001). Further guidance is provided in the two accompanying texts dealing with protection of groundwaters and surface waters as drinking-water sources (see Foreword).

Water leaving water treatment plants should meet stringent criteria to provide assurance that pathogens are reduced to acceptable levels. The objective is not to provide sterile water to the consumer (which is neither practicable nor beneficial). However, the bacteriological content of drinking-water leaving treatment plants should contain only very low levels of heterotrophic and aerobic spore-forming microorganisms. Low levels of these organisms indicate that the treatment and disinfection processes have been effective in removing or inactivating most pathogens. It is possible to produce drinking-water leaving the treatment plant with less than 10 colony forming units (cfu)/ml of heterotrophic microorganisms. At this level of treatment, total coliforms, thermotolerant coliforms and *E. coli* should be absent. They are much less resistant to disinfection than other heterotrophic and aerobic spore-forming microorganisms, and their presence would be an immediate indication of an unacceptable quality.

There are, however, numerous reports in the literature concerning the presence of low levels of pathogens in treated drinking-water. These occurrences usually correspond to the use of contaminated surface water sources (rivers and lakes) or to groundwater affected by contaminated surface waters. Infectious viruses have been found in treated drinking-water that meets regulations (Payment & Armon, 1989; Gerba & Rose, 1990). Oocysts of *Giardia* and *Cryptosporidium* have been found repeatedly in treated waters, but their infectivity was often undetermined and their health significance unknown.

The reasons for these findings, other than elevated source water contamination, include inefficient coagulation, inefficient filtration (e.g. failure in filtration, backwash recycling and poor maturation of filters) and poor disinfection (e.g. no free-residual disinfectant and short contact times). Pathogenic microorganisms that evade treatment and enter the distribution system may survive and be the source of an important level of endemic disease in the population (Payment et al., 1991; 1997). Therefore, the selection of appropriate processes for the removal of pathogens and the adoption of Water Safety Plan principles in operating these treatment barriers is important for safe water supply.

### 1.3.2 Growth of microorganisms in the distribution system

Water treatment processes are capable of reducing heterotrophic microorganisms to less than 10 cfu/ml, although waters from most treatment works typically contain higher numbers. Some viable organisms remaining in the water will multiply if nutrients are available, especially in waters that are above 15°C, and may lead to the formation of biofilms on internal surfaces. Biofilms typically contain numerous free-living heterotrophic bacteria, fungi, protozoa, nematodes and crustaceans. Older systems may contain deposits and sediments formed by the internal corrosion of metal pipes and insufficient water treatment; they may also contain many microorganisms. The multiplication of bacteria in a piped distribution system is driven by the availability of organic and inorganic nutrients in the conveyed water and in surface deposits. This subject is discussed in Chapter 2, where practical guidance is provided for the operation of treatment processes to minimize microbial growth in distribution systems.

Most microorganisms developing within the distribution network are harmless. Exceptions include *Legionella* and *Mycobacterium avium* complex, which are discussed below. There are no reports of public health problems arising from ingestion of opportunistic pathogens (e.g. *Aeromonas* and *Pseudomonas*) found in drinking-water biofilms. *Pseudomonas* and *Aeromonas* strains present in water usually do not have the same genetic pattern as those found in clinical cases during gastrointestinal infections (Havelaar et al., 1992).

Although these organisms have not been implicated in waterborne outbreaks, *Pseudomonas* has been identified as the cause of several skin infections associated with swimming pools, hot tubs and other spa facilities (WHO, 2000).

*Legionella* and the *M. avium* complex merit special attention. *Legionella* in a piped distribution system can grow to significant numbers in warm waters and can colonise water heaters, hot tubs, hot-water lines and shower heads. The organism is also associated with cooling towers or evaporative condensers. Special precautions need to be taken to prevent or control *Legionella* in environments such as hospitals and health care facilities, because aerosols generated by showers or spas can be a route of infection, and contamination with *Legionella* can be a significant source of nosocomial (hospital-acquired) infections. This subject is beyond the scope of this document, but a summary of knowledge and precautions is available in a companion text (*Legionella and the Prevention of Legionellosis*, see Foreword).

The *M. avium* complex is a group of bacteria that are opportunistic pathogens in man, producing symptoms similar to *M. tuberculosis* (French, Benator & Gordin, 1997; Horsburgh et al., 1994). They are ubiquitous in soil, food and water, have been found in biofilms and are quite resistant to disinfection. Strains of these microorganisms that are found in the environment have been shown to cause disease in immunocompromised patients.

*Acanthamoeba* and *Naegleria* are free-living amoebae (single-celled microscopic animals) found commonly in soil and water habitats. Both have been associated with water-borne infections but not through drinking. Species of *Acanthamoeba* can cause contact lens related keratitis, with the source of contamination being linked to poorly maintained lens storage cases (Stehr-Green et al., 1987). *Naegleria fowleri* is the causative agent of primary amoebic meningoencephalitis. Infection occurs after swimming or activities that cause nasal inhalation of contaminated water. *Naegleria fowleri* is typically thermophilic, growing in water up to 45° C. Although drinking-water has not been demonstrated as a source of infection, *Naegleria fowleri* has been found in distribution systems, with detection correlated with heterotrophic plate counts and the absence of free chlorine residuals (Esterman et al., 1984).

Free living amoebae such as *Acanthamoeba* and *Naegleria* can also harbour bacterial pathogens such as *Legionella* and mycobacteria, and may play a role in the survival of these organisms in drinking-water environments and in their pathogenesis (Lee & West, 1991; Steinert et al., 1998).

Bacteria present in the water and on surfaces are at the base of a food-chain for other organisms such as fungi, protozoa, worms and crustaceans. Chapter 6 discusses the occurrence and significance of metazoan (many-celled) animals in treated drinking-water distribution systems. In temperate countries, no population of pathogenic animals has been found in a distribution system. In tropical climates, the only potential health hazard that has been postulated

(WHO, 1996) arises in countries where water fleas (*Cyclops*) are the intermediate host of the guinea worm (*Dracunculus medinensis*). However, this is a theoretical risk as there is no evidence that guinea worm transmission occurs from piped drinking-water supplies. Generally, the presence of animals has largely been regarded by water suppliers as an "aesthetic" problem, either directly or through their association with discoloured water (see Chapter 6 for further discussion).

### 1.3.3 The fate of pathogens gaining access to distribution systems

Biofilms, sediments and corrosion products may harbour pathogenic microorganisms introduced through inefficient treatment or breaches of the integrity of the distribution system. Buried in the sediments or embedded in the biofilm, pathogens could be released during repairs and cleaning operations, or by erosion caused by sudden changes in flow patterns. Survival depends on their nature and the microbial activity in the biofilm. Only a few pathogenic bacterial species may multiply if favourable conditions, such as warm water and appropriate nutrients, are present (LeChevallier et al., 1999a; 1999b).

Viruses and protozoan parasites are obligate parasites and they need a human or animal host to multiply. If they enter the pipe network, they can only survive for a limited period; the infective dose for human hosts is likely to be reached only if large accumulations occur within system deposits. Such accumulations may occur as a result of cross-connections, backflow or contamination (see Box 1.1).

Although there are currently no reports of health effects directly attributed to the long-term survival of pathogens within a distribution system, such organisms have been shown to persist within biofilms, thereby presenting a potential underlying health concern to consumers (Szewzyk et al., 2000). Biofilms contain many sorption sites that can bind and accumulate organic and inorganic contaminants, as well as particulate and colloidal matter (Flemming, 1995). Within biofilms, microbial pathogens can be protected from biological, physical, chemical and environmental stresses, including predation, desiccation and changes or fluxes in the environment (Buswell et al., 1998; Walker et al., 1995).

Bacterial pathogens such as *Helicobacter pylori* (Mackay et al., 1998), enterotoxigenic *E. coli* (Szewzyk et al., 1994), *Salmonella typhimurium* (Armon et al. 1997) and *Campylobacter* species (Buswell et al., 1998) can persist within biofilms formed in experimental laboratory systems. The potential therefore exists for such pathogens to accumulate and persist within a municipal distribution system, although so far they have not been isolated directly from such systems. Model enteric viruses (B40-8 and MS2 bacteriophages) have also been shown to accumulate and persist within biofilms formed in the laboratory (Storey & Ashbolt, 2001), although again these organisms have not been isolated directly from a municipal water distribution system. The interaction of viruses with pipe biofilms has been neglected or ignored in the past (Ford, 1999); however, recent research has demonstrated its potential significance (Storey and Ashbolt, 2003b)

Problems may therefore arise in distribution pipe systems when clusters of biofilm-associated pathogens become detached from either substrata or biofilm matrices by physical, chemical or biological processes. Detached biomass could compromise the microbiological quality of distribution waters by providing a continual contamination of the bulk water through the release of sorbed pathogens and indicators. These mobilized pathogens, which may exist at concentrations greater than an infective dose, have the potential to reach consumers through the ingestion of contaminated water or food contaminated with such water, inhalation of aerosols or breaks in the skin (Ashbolt, 1995). For example, in a risk model that has been developed for the distribution of recycled water there is evidence to suggest that, even during normal operating conditions (1 virus per 100 l of recycled water), enteric viruses may accumulate within distribution pipe biofilms in sufficient numbers to present a risk to consumers should a biofilm slough off from the pipe (Storey & Ashbolt, 2003a). These studies support the view that preventing the accumulation of deposits and biofilms in a distribution system should be an important component of a water safety plan (see Chapter 7).

### 1.3.4 Households and large building systems

Water usage, pipe materials and water-purification devices (point-of-use or point-of-entry) can positively or negatively affect water quality in buildings.

Water in household or building pipes can stagnate for long periods, leading to deterioration in the microbial and chemical quality of the water. Buildings at risk include schools during a vacation period, hotels with intermittent room occupancy, large buildings relatively unoccupied during weekends and sections of hospitals closed for long periods. These situations require planning from responsible authorities to ensure public health protection.

**Box 1.1.** Persistence of *Cryptosporidium* oocysts in distribution after an outbreak of cryptosporidiosis.

During March 2000, the town of Clitheroe in Lancashire, England was affected by an outbreak of cryptosporidiosis that affected at least 58 people. Most of the cases resided in an area supplied by a single spring source. The supply provided water to 17 252 people and was chlorinated but not filtered. It rapidly became clear that the source of contamination was cattle grazing near the spring. As soon as the water source was implicated in the outbreak, the supply was switched to a much larger and better-treated supply.

Of interest was the persistence of oocysts in distribution long after the source had been switched. The source was changed on the evening after the first outbreak meeting on 16 March and the system was flushed by opening fire hydrants in the town. For the following days, multiple (up to 23 per day) 10-litre samples were collected from consumers' taps. Despite the flushing, oocysts were detected in tap samples for 10 consecutive days, although in decreasing numbers. However, on 20 March there was a peak (mean 0.2 oocysts/l) following a burst main. Because of this, the public were advised on 21 March to boil all drinking-water.

On 26 and 27 March, all samples were negative and it was decided to reduce the number of daily samples. However, on the following day, two of three samples were positive (mean 0.23 oocysts/l) and further samples were positive over the following few days. This increase coincided with a decision to sample from fire hydrants rather than consumers' taps.

This outbreak demonstrated the importance of the distribution system, even in outbreaks due to source water contamination. The pathogen was retained in the system even after vigorous flushing. Although the epidemiological evidence suggested that nobody became infected after the change in supply, persistence of oocysts led to the boil water advice. Partly based on the increased counts in water from fire hydrant samples, the investigators suggested that oocysts were being trapped in biofilm in the distribution network and then being released back into the supply.

Source: Howe et al. (2002).

The presence of properly designed and maintained water purification devices offers some level of protection to the consumer. Filters capable of removing micron-size particles or smaller can provide an effective barrier against incoming contaminated water and bacterial and parasitic pathogens. They can be used to reduce risks for vulnerable individuals (e.g. people with acquired immune deficiency syndrome (AIDS) and other immunocompromised individuals). They may also be useful in areas where water treatment and distribution are not reliable (e.g. loss of pressure, inadequate or intermittent treatment). In these cases, filtration should be followed by disinfection (e.g. chlorine or ultraviolet radiation).

Point-of-use and point-of-entry filtering devices can retain large numbers of microorganisms as well as particulate matter. Multiplication of heterotrophic bacteria is frequent in such units, but health effects have not been reported. The issue of pathogens captured in these units has been studied extensively (Geldreich & Reasoner, 1989). Although some pathogens can survive in the matrix of filters, they are usually overcome by the growth of heterotrophic bacteria that have a much higher capacity to multiply in this environment.

### 1.3.5 Controlling microorganisms in distribution systems

Current practice in many countries is to use disinfectant residuals to control the growth of microorganisms in distribution systems and to act as a final barrier, to help maintain the microbial safety of the water. The various options for disinfection are discussed in Chapter 2. Realistic residual concentrations only inactivate the least resistant microorganisms such as *E. coli* and the thermotolerant coliforms that are used as the main indicators of water safety (Payment, 1999). Absence of coliforms may create a false sense of security because many viral and parasitic pathogens are resistant to a low level of disinfectant. Therefore, the maintenance of a disinfectant residual or an increase in disinfectant dose should never be regarded as a substitute for the rigorous application of the operational and maintenance practices described in this review. However, the loss of chlorine residual can be used as an indicator of intrusion if an appropriate monitoring frequency is established, especially if continuous monitoring facilities are in place in the distribution system.

In some countries and in many small community-managed piped water supplies, no disinfectant residual is applied to maintain quality during distribution. In these cases, prevention of the ingress of pathogenic microorganisms must be assured, to protect water quality. This relies on regular sanitary inspection of distribution systems to identify potential leaks or parts of the system where ingress could occur. In addition, attention should be paid to areas where faecal material builds up close to the pipe and where surface or soil water would be likely to become contaminated. The results of the sanitary inspection should be used to define preventive maintenance and remedial actions (where necessary). Maintenance of water quality in nondisinfected piped-water supplies requires proper training of system operators and managers and, in the case of community-managed supplies, on-going support through surveillance.

In large systems, particularly where disinfectant residual is not maintained, nutrient levels should be controlled to reduce the potential for biofilm growth

## 1.4 TRADITIONAL APPROACHES TO MICROBIAL MONITORING IN DISTRIBUTION SYSTEMS

### 1.4.1 Regulations and guidelines for microbiological parameters

*Total coliforms*

Coliforms have been used extensively as a basis for regulating the microbial quality of drinking-water. Initially total coliforms were used as indicators of faecal contamination and hence of the possible presence of enteric pathogens. However, many species of bacteria in the total coliform group survive and grow in the environment, and their value as an indicator of faecal contamination has been questioned by many regulatory agencies. Strains of total coliform bacteria may colonise surfaces within systems and become part of a biofilm (Power & Nagy, 1989; LeChevallier, 1990). The environmental conditions that favour this process are water temperatures greater than 15°C, neutral pH and adequate concentrations of assimilable organic carbon (AOC). In temperate climates, growth events typically occur during the summer months, but in tropical or subtropical climates they may occur year-round.

Their ability to thrive in the environment or in a drinking-water distribution system makes total coliforms an unreliable index of faecal contamination. However, total coliforms can be used in operational monitoring as a measure of deterioration of water quality through distribution systems. Detection of these organisms can reveal microbial growth and possible biofilm formation, as well as ingress of foreign material including soil. However, heterotrophic plate counts (HPCs) detect a wider range of organisms and are generally considered better indicators for these conditions than total coliforms.

*Escherichia coli and thermotolerant coliforms*

*Escherichia coli* (*E. coli*) is the faecal indicator of choice used in WHO *Guidelines for Drinking-water Quality* (WHO, 2004) and several countries are including this organism in their regulations as the primary indicator of faecal pollution. Current data suggest that *E. coli* is almost exclusively derived from the faeces of warm-blooded animals. Its presence in drinking-water is interpreted as an indication of recent or substantial post-treatment faecal contamination or inadequate treatment. Thermotolerant coliforms include *E. coli* and also some types of *Citrobacter*, *Klebsiella* and *Enterobacter*. Although thermotolerant species other than *E. coli* can include environmental organisms, populations of thermotolerant coliforms detected in most waters are predominantly composed of *E. coli*. As a result, thermotolerant coliforms are regarded as a less reliable but acceptable indicator of faecal pollution.

In using *E. coli* or thermotolerant coliforms as an indicator of faecal pollution, a number of issues need to be considered. First, although *E. coli* does not readily grow outside the gut of warm-blooded animals in temperate regions, there is some evidence to suggest that it may grow in the natural environment in tropical regions (Byanppanahalli & Fujioka, 1998). However, in most cases, *E. coli* would be outcompeted by other environmental bacteria; therefore, whether growth occurs in nature is questionable. If such growth were to be found in certain tropical regions, then regulations would have to be based upon alternative indicators of post-treatment faecal contamination in storage and distribution systems, such as intestinal enterococci and *Clostridium perfringens* spores (Ashbolt, Grabow & Snozzi, 2001).

Second, *E. coli* is extremely sensitive to disinfection (LeChevallier et al., 2003). Its presence in a water sample is a sure sign of a major deficiency in the treatment or integrity of the distribution system. However, its absence does not by itself provide sufficient assurance that the water is free of risks from microbes. Many viral and protozoan pathogens are significantly more resistant to disinfection and may survive exposure to disinfectant that inactivates *E. coli*. Ingress of sewage into a distribution system conveying water with a disinfectant residual might not be detected using *E. coli* alone: these bacteria might be inactivated while other pathogens remained viable.

### *Heterotrophic plate count*

The HPC was among the first parameters used to monitor the microbial quality of drinking-water. Following the work of Koch in the late 1800s, HPC was used to monitor the safety of finished drinking-water. However, in recent times, HPC has become an indicator of general water quality within distribution systems (WHO, 2003).

Heterotrophic microorganisms are indigenous to water (and biofilms) and are always present in greater concentrations than coliform bacteria in distribution and storage systems. An increase in HPC indicates treatment breakthrough, post-treatment contamination, growth within the water conveyed by the distribution system or the presence of deposits and biofilms in the system. A sudden increase in HPCs above historic baseline values should trigger actions to investigate and, if necessary, remediate the situation. There is no evidence that heterotrophic microrganisms in distribution systems are responsible for public health effects in the general population through ingestion of drinking-water (WHO, 2003).

Some countries use a nonmandatory maximum HPC of 500 cfu/ml at 35°C, because concentrations greater than this interfere with the recovery of coliform bacteria by membrane filtration techniques based on lactose fermentation. However, newer coliform detection methods based on the metabolism of chromogenic substrates are not prone to this interference.

## 1.4.2 Principles of microbial monitoring in distribution systems

The purpose of microbial monitoring programmes in distribution systems is to ensure that water supplies comply with applicable guidelines, standards or regulations.

Guidance on methods for sampling and monitoring is part of internationally accepted documents (ISO, 1980–98). Promulgated requirements or recommendations usually appear simplistic. They are often based on population-served criteria such as "*4 samples per month, if population is less than 5000*". Programmes based on such criteria are ineffective for monitoring the quality of the water delivered to all consumers.

In theory, microbial monitoring could be achieved by a programme of frequent monitoring at every storage reservoir and service connection throughout the system. However, such a strategy would be prohibitively expensive and could only verify that the water was safe after it was supplied, because the identification and enumeration of microorganisms is too slow to be suitable for early warning or control purposes.

One way to monitor effectively is to perform both routine sampling for microbial quality and real-time (and possibly online) monitoring of parameters linked to microbial quality at selected locations throughout the storage and distribution system. With a good knowledge of the system's hydraulics this approach can be cost-effective and can quickly provide warnings of system failures related to health risks. Potential surrogate parameters are free chlorine, water pressure, dissolved oxygen and turbidity. Sudden anomalous changes in any of these parameters may indicate a problem with the system. A monitoring programme should include directions on data interpretation and corrective actions to be taken when limits are exceeded.

The function of microbial monitoring in distribution is recognized in the water supply plans described in Chapter 7. A water safety plan for the management of distribution systems involves three types of monitoring (see Section 7.3.3):

- operational monitoring to support on-going management of the safety of the system;
- process validation for the design of treatment processes and other control measures;
- verification to check that the entire water supply system is functioning correctly.

Routine microbial monitoring normally fulfils the verification role by acting as a final check of water safety. It verifies that the system is functioning properly; it should not be relied upon for operational control.

Periodic sanitary surveys of the storage and distribution system are an important part of any water safety plan. Such surveys are inexpensive to carry out and can complement water quality measurements. They are essential for small community-managed supplies where verification of water quality may be infrequent. Chapters 4 and 7 provide guidance on sanitary surveys and routine inspections.

## 1.5 SUMMARY

Good quality drinking-water can suffer serious contamination in distribution systems because of breaches in the integrity of the pipework and storage reservoirs. Many outbreaks of waterborne disease have been attributed to such events.

All distribution systems harbour active populations of microorganisms that do not threaten public health. Nevertheless, in many countries it is usual to maintain a disinfectant residual to control bacterial proliferation in the body of water supplied. This will limit the development of tastes and odours produced by biofilms, and may also inactivate low levels of some pathogens that gain entry to the network. Although there are currently no reports of health effects directly attributed to the long-term survival of pathogens within a distribution system, there is a potential for such organisms to accumulate and persist within biofilms. Experimental studies confirm this potential and support the view that preventing the accumulation of deposits and biofilms in a distribution system should be an important component of a water safety plan.

The routine monitoring of microbial indicators, such as *E. coli* (or alternatively thermotolerant coliforms), can be used as part of a final check on water quality (verification). Such monitoring should not be the only method for managing risk or supporting decisions about the operation of the distribution system. Safe drinking-water is best achieved by adopting a holistic approach based on design, operational practices and maintenance procedures that takes account of biological hazards. This approach is the basis of the water safety plans described in Chapter 7. Monitoring has an important role as part of water safety plans and should include parameters that are capable of revealing both potential contamination (due to lack of system integrity) and actual contamination.

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