Chapter 6

MONITORING THE QUALITY OF DRINKING WATER DURING STORAGE AND DISTRIBUTION

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6.1 Introduction

Following abstraction and treatment water becomes a vulnerable and perishable product. It is vulnerable in that the integrity of systems used for the storage and distribution of water can be damaged and contamination through ingress can occur. It is perishable in that its microbial quality can deteriorate due to the bacteria remaining after treatment growing on the residual nutrient in the water. Water can therefore be regarded as having a finite life.

The rate at which quality deteriorates can be controlled by adding a preservative (disinfectant residual), or by the use of advanced treatment to remove as much biodegradable organic carbon as possible from the water. However, these measures will be to no avail, if the distribution or storage-systems are contaminated or permit ingress. To get the maximum degree of protection the product (water) and the packaging (tanks and pipes) must be clean and intact.

The importance of quality changes in distribution is based upon evidence concerning the frequency and extent of known quality changes and their impact upon human health. Thus, for example, a significant proportion of recognised piped drinking water-related disease outbreaks are related to quality deterioration in distribution (Ainsworth, 2002; Craun and Calderon, 2001). However, most water supply world-wide is unreliable because of, for example, intermittence and so household management is common. This may involve only plumbed in household storage tanks or alternatives, which involve extensive
manual handling. Because the contamination that arises is local in character it is unlikely to give rise to detectable outbreaks of disease but significant evidence exists that quality changes in such circumstances may be extreme and respond to the extent of handling (Quick et al., 1999).

6.2 Piped distribution systems

Piped distribution systems for drinking water are as important to the quality and safety of drinking water as the treatment itself. Water entering the distribution system must be microbiologically safe and ideally should be biologically stable. The distribution system itself must provide a secure barrier to post-treatment contamination as the water is transported to the user. Residual disinfection will provide partial protection against recontamination, but may also act to mask the presence of such contamination. On a global scale, however, mishandling within the home is likely to be the most significant source of fouling. This section describes the sources of contamination progressing from treated water leaving the treatment plant, to deterioration of water quality during storage and distribution. Non-piped systems are dealt with in a separate section.

6.2.1 Inadequately treated water entering the distribution system

Sporadic occurrences of source water of high turbidity that overwhelm the treatment train, or microorganism breakthrough for example resulting from sub-optimal filtration following filter backwashing, can introduce enteric pathogens into the distribution system. These may be in sufficient numbers to cause detectable cases of gastrointestinal illness in the population served (MacKenzie et al., 1994). It should be recalled that the frequency of such events in developed and developing countries is likely to be far greater than that implied by the number of outbreaks presently detected (see Chapter 7). Such occurrences are often rainfall driven and may be inter-related. For example exceptionally high pathogen loadings may arise from surface runoff following rainfall at the same time that overall filter efficiency decreases and the need for backwashing increases because of the concurrent high turbidity loadings (see Chapters 4 and 5).
6.2.2 Integrity of the distribution system

Disease outbreaks have been traced to cross connections in spite of the fact that water leaving the plant was deemed to be safe. In general, there are four types of cross connections:

- **Infiltration.** In this situation contaminated sub-surface water is drawn into the distribution system. In order for this to happen three conditions must be in place. First, contaminated water must be present in the sub-surface material surrounding the distribution system, possibly from a leaking sanitary, storm or combined sewer. Secondly, there must be an adjacent low-pressure zone within the system. These zones can arise through high water usage resulting from fire fighting or other peak demands, decreased flow arising from restrictions in the system, pump failures or intermittent operation of the treatment plant. More recent evidence points to the role of pressure surges, in otherwise properly operated systems, in creating transient low pressure that may lead to the ingress of contaminants (LeChevallier, 1999). Thirdly, there must be a route for contaminated water to enter the system. This can occur through pinholes caused by corrosion, cracks or outright breaks or leaking joints in the wall of the mains. If these three situations occur simultaneously then it is likely that contaminated water will enter the distribution system. Leakage rates are typically high, with even well operated systems experiencing rates of 10 – 20% (LeChevallier, 1999; WHO and UNICEF, 2000). This is likely to be associated with a relatively large number of points of leakage and therefore present an increased risk of intrusion of pathogenic organisms.

- **Back siphonage.** In this situation faecally contaminated surface water is drawn into the distribution system or storage reservoir through a back flow mechanism. In order for this to take place two conditions must occur simultaneously. Firstly, there must be a reduction in line pressure as described above. Secondly, there must be a physical link between contaminated water and the storage and distribution system. Open taps connected to hoses that are submerged in pools of water may provide this link. Back flow preventers are available to stop such occurrences. Plumbing codes should require air gaps between taps and the brim of receptacles. The general conclusion stresses the importance of good domestic plumbing practice.

- **Open drinking water storage reservoirs.** Microbial contamination can also be introduced into the distribution system through open treated-water storage reservoirs (Geldreich, 1996). For example, waterborne outbreaks
have occurred in communities where birds contaminated the water either because the reservoir was uncovered or because they gained access to the reservoir through unscreened roof vents. Uncovered reservoirs can also permit the growth of toxin-forming cyanobacteria.

- **Line construction and repair.** When existing mains are repaired or replaced or when new water mains are installed strict protocols involving disinfection and flushing must be followed to prevent the introduction of contaminated soil or debris into the system (e.g. AWWA, 1986). These protocols generally cover six areas of concern:
  1. Protection of pipe sections at the site.
  2. Restriction on the types of joint sealing materials used.
  3. Preliminary flushing of pipe sections.
  4. Disinfection of pipe sections.
  5. Final flushing of pipe sections.
  6. Bacteriological testing to confirm disinfection.

If these procedures are not adhered to pathogens may gain access to the system. Construction materials, such as wood embedded in pipe sections, have also been identified as a source of microbial contamination and provide an adequate supply of nutrients to support bacterial re-growth (Martin et al., 1982).

In each scenario, if the contaminated water contains enteric pathogens then it is likely that consumers will be exposed to them. Even where disinfectant residuals are employed to limit microbial occurrence it may be inadequate to overcome the contamination or may be ineffective against some or all of the pathogen types introduced. As a result, pathogens may occur in concentrations that could lead to infection and illness. In many developing countries drinking water is supplied intermittently either as a cost-saving measure or because of water shortages. Under such conditions the resulting low water pressure will allow the ingress of contaminated water into the system through breaks, cracks, joints and pinholes in the walls of the system.

In the context of monitoring it should be noted that the use of residual disinfectants to control such problems may lead to an inaccurate estimation of their occurrence. This is because the microbial indicator parameters most frequently used for monitoring are among the most sensitive of the organisms of interest, leading to a potential situation where the indicator parameter is absent.
but pathogens may be present. Thus, neither the occurrence nor the severity of contamination will be properly identified.

6.2.3 **Microbial re-growth in the distribution system**

Even though treated drinking water may be free of faecal indicator organisms and detectable enteric pathogens and therefore present a tolerable level of risk of enteric illness, drinking water entering the distribution system may contain free-living amoebae and environmental strains of various bacterial species, often referred to as heterotrophic bacteria. Under favourable conditions amoebae and heterotrophs will colonise a distribution system and form biofilms.

Many environmental strains of coliform bacteria such as *Citrobacter*, *Enterobacter* and *Klebsiella* may also colonise distribution systems (Martin et al., 1982). However, it is generally agreed that water temperatures and nutrient concentrations are not elevated enough to support the growth of *E. coli* (or enteric pathogenic bacteria) in biofilms (Geldreich and LeChevallier, 1999). Thus the presence of *E. coli* should be considered as evidence of recent faecal contamination of drinking water.

Many species of bacteria and free-living amoebae can occur in biofilms within distribution systems including certain opportunistic pathogens. There is inadequate evidence at present to implicate the occurrence of these microorganisms from biofilms (excepting for example, *Legionella* or *Mycobacterium*) with adverse health effects in humans with the possible exception of immuno-compromised population groups (reviewed by Geldreich, 1996).

6.3 **Non-piped distribution systems**

Most of the population of the globe obtain their water through non-piped systems and of the remainder the majority are supplied through systems that require some form of storage and/or handling before use, thereby increasing the possibility of contamination. Even where a reliable piped supply is the norm, occasional interruptions occur (*e.g.* extreme weather events that cause major line breaks and force adoption of household handling). From a public health viewpoint it is therefore essential to respond to contamination that occurs through the chain of supply up to the point of use and to consider all forms of water supply used by the population.
Point sources of water such as tubewells, dug wells and protected springs represent a very significant proportion of the ‘improved’ water supplies provided to communities in developing countries (WHO and UNICEF, 2000). Such supplies are very common in rural areas and may also represent a very significant proportion of the water supplies available and used for domestic purposes (including drinking) by low-income urban populations (WHO and UNICEF, 2000; Howard et al., 1999; Ahmed and Hossain, 1997). The quality of such sources is often very variable and they frequently show gross faecal contamination, particularly during wet seasons (Wright, 1986; Barrett et al., 2000). The public health consequences of consumption of contaminated water from point sources can be severe both in relation to endemic and epidemic disease (Pedley and Howard, 1997). The control of the quality of drinking water from such sources is important in reducing public health risks, but requires greater emphasis on support to community management in order to improve operation and maintenance, and also significant user education.

As point water sources are often found in areas that also rely on on-site sanitation, sub-surface leaching is frequently identified as being a principal source of contamination (Melian et al., 1999; Rahman, 1996). However, there is increasing evidence that deterioration in sanitary completion measures and preferential flow paths are more important in causing microbial contamination (Howard et al., 2001a; Gelinas et al., 1996; Rojas et al., 1995). Different technologies have different vulnerability to contamination depending, largely, on the depth of abstraction (ARGOSS, 2001).

Many people world-wide rely on water supplied by tankers or other forms of vendor supplies (Whittington et al., 1991). The water in such supplies may come from hydrants connected to utility supplies or may be drawn from alternative sources. In many cases, the consumer will not be aware of the source of the water and there may be significant concerns about the quality of water (Lloyd et al., 1991). Where the water is supplied from hydrants via utility piped water supplies, basic good hygiene practices, such as regular cleaning and disinfection of the tank and sanitary storage of the connecting hoses is usually adequate to maintain quality. Studies in Ghana, showed that the quality of water in tanker trucks collecting water from utility hydrants was the same as the piped water in Kumasi and only marginally less good in the capital Accra (Jabulo, pers. comm.). In the Ghana study and also studies in Uganda (Howard and Luyima, 2000), however, it has been shown that the quality of water supplied by other vendors, such as those selling from jerry cans or small fixed tanks, is much worse and represents highly degraded water quality.
In non-piped systems drinking water is typically either carried to the home or is transported by truck or cart. The contamination of the water, usually as a result of poor hygiene is common. Source contamination can then be augmented at each point of handling through collection and transport (VanDerslice and Briscoe, 1993). However, because such contamination is by definition local in nature, it is unlikely to lead to large-scale single source outbreaks and therefore unlikely to be detected or reasonably estimated.

Poor hygiene in the home is another, potentially significant source of drinking water contamination. In many cases, contamination significantly increases from source to household (WHO, 1997). This is of particular concern in communities without reliable piped water to within dwellings which, therefore, rely upon water storage containers. Evidence is accumulating for both the impact of such contamination on human health and for the effectiveness of interventions at this level in protecting and improving human health (Semenza et al., 1998). Such interventions include the use of household water disinfection technologies, including chlorination and solar disinfection (see Chapter 5; Sobsey, 2002). They also include hygiene education interventions geared to the maintenance of water quality during transport and storage. Such interventions may include the testing of water and participatory approaches to health education, which, have proven successful in both rural and urban areas (Breslin, 2000).

The selection of whether water treatment or hygiene education interventions are most appropriate depends in part on the quality of the source water. If it is good, then greater effort may be placed on promoting safe handling, whereas poor source water quality greater effort may be placed on household treatment. Where household disinfection is promoted, it is essential that water quality programmes provide educational information on disinfecting drinking water in the home and maintaining the quality and safety of the water following disinfection. There is considerable evidence to suggest that this approach is effective at reducing contamination and the spread of enteric illness (Sobsey, 2002; Forget and Sanchez-Bain, 1999; Quick et al., 1999; Reiff et al., 1996).

6.4 Approaches to sampling in piped distribution systems

Strategies for monitoring the microbiological quality of water in supply must be designed to allow the best possible chance of detecting reductions in microbial quality (Ainsworth et al., 2002). It is vital, therefore, to ensure that the samples taken are representative of the quality in the distribution network.
In formulating a strategy the factors outlined in the following subsections need to be considered (ISO, 1991).

6.4.1 Choice of indicator parameter

Traditionally, microbial indicators of faecal pollution such as total coliforms and \textit{E. coli} have been the determinants used. Most national and international microbial standards for water in supply are expressed in terms of these organisms. Measurement of the numbers of heterotrophic bacteria provide further valuable, but often under-utilised, additional information. Secondary microbial parameters, for example, enterococci and clostridia, being more resistant to disinfection, may also be used to try and gain better insight into the source of the contamination or where particular sources of contamination are suspected or known to cause problems. These secondary parameters are most often used, therefore, as part of investigations where a failure of quality, in terms of the detection of coliform bacteria, has been detected. The practice of application of a residual disinfectant such as chlorine has a significant impact upon the adequacy of alternative indicators as outlined above. Since the most common microbial indicators of faecal pollution (\textit{E. coli} or thermotolerant coliforms and total coliforms) are very sensitive to chlorine their detection implies the likelihood of either recent or substantial faecal contamination with attendant health risks. Nevertheless, because coliform bacteria are so sensitive to chlorine their absence provides no guarantee that pathogens such as enteric protozoa and viruses, which are more resistant to chlorine, are also absent.

In any faecal contamination event microorganisms, whether introduced by inadequate treatment or post-treatment contamination, are not distributed evenly throughout the distribution system but are typically clumped (Gale, 1996a). In these situations the probability of detecting faecal indicator bacteria in the relatively few samples collected from the distribution system during routine sampling is substantially reduced. Hence quantitative measurements of contamination, such as membrane filtration (MF) or most probable number (MPN) methods, may provide a poor estimate of the overall density of indicator bacteria. Frequency-of-occurrence monitoring, based on the Presence/Absence (P/A) test, can provide a better estimate of water quality in general (Pipes and Christian, 1984; Clark, 1980). In this method the frequency of positive samples detected during routine sampling during a reporting period is compared with acceptable frequencies of positive samples specified in the applicable water quality standards. Where such standards are based upon \textit{E. coli} or thermotolerant coliforms, their confirmed presence usually leads to an immediate boil water advisory and corrective actions. Standards based upon the presence of total coliforms specify an acceptable frequency of positive samples
(for example 5%) before resampling and possible corrective actions are required. Comparative studies of the P/A and MF methods demonstrate that the P/A method can maximise the detection of faecal indicator bacteria (Clark, 1990; Geldreich, 1996). It also allows more samples to be analysed within a reporting period because the test is simpler, faster and less expensive than the quantitative methods noted above (see Chapter 2.2.9). Commercial P/A kits for faecal indicator bacteria are available.

More conservative microbial parameters (i.e. parameters of quality deterioration that may be detected before actual faecal contamination occurs) are logically preferred but most present practical/logistical problems. The most frequently used alternative for distribution systems is presently the heterotrophic plate count. Whilst taxonomically imprecise this is relatively widely available and applicable. Its value is principally associated with changes and trends in counts retrieved from a given system rather than comparison with numeric reference values and it therefore requires relatively dense sampling networks (in time and space) to provide useful information. Measuring the numbers of heterotrophic bacteria present in a supply can be a useful indicator of changes such as increased re-growth potential, increased biofilm activity, extended retention times or stagnation and a breakdown of integrity of the system. Following trends in the numbers of heterotrophs may therefore be useful in prompting, for example, a programme of mains flushing or cleaning.

Non-microbial parameters may also be suitable for this purpose and also require comparison on changes and trends and therefore relatively dense sampling networks. The most frequently used examples include conductivity/total dissolved solids, turbidity and chlorine residual (where chlorine is applied). Where chlorine residuals are used, measurement of this residual can often be a more rapid indication of problems than microbial parameters. A sudden disappearance of an otherwise stable residual can indicate ingress of contamination with a high organic loading. Alternatively, difficulties in maintaining residuals at points in a distribution system or a gradual disappearance of residual may indicate that the water or pipe work has a high oxidant demand due to re-growth of bacteria in the water or biofilm growth.

Routine monitoring of distributed water for particular groups of bacteria or specific pathogens is rarely considered worthwhile or necessary. However, in the Netherlands guidelines for the numbers of aeromonads in final waters and in distribution have been issued to act as an indication that better maintenance of sand filters or that better removal of methane from anaerobic groundwater sources is required. In this context aeromonads are acting as a sensitive indicator of the potential for re-growth to occur within the network (see Chapter 2.2.8).
6.4.2 Location of sampling points

The two principal considerations in the location of sampling points are whether fixed or variable locations (or a mixture of these) are to be employed, and whether sampling is to occur from normal access points (such as consumer taps), from dedicated but otherwise normal locations or from structures dedicated exclusively for this purpose. The purpose of monitoring and especially whether in response to statutory requirements or for public health investigatory purposes will have a significant impact on the choices made.

Sampling locations should be chosen to provide a means of characterising water quality in all parts of the system. For this reason a supply system may be divided into a series of zones on the basis of geographical area, the size of the population served or specific areas of the pipe network. Sampling points are then identified within each zone to try and ensure that representative samples are taken. Sampling points will be chosen for two reasons. One will be to satisfy statutory responsibilities and the other for strategic or operational purposes. In the latter, a water supplier may for example be trying to obtain more information about an area that has, in the past, yielded frequent coliform failures or elevated counts of heterotrophs.

Fixed sampling points are frequently used, and may be chosen because of ease of access. Often these points are located within public buildings, or in the premises of public services, such as fire-stations. The use of fixed sampling points alone can be regarded as unsatisfactory, since they may not give a representative view of what is happening in all parts of the distribution system or zones. To overcome this, additional samples may be taken from other outlets chosen at random and these usually include the mains tap in the houses of consumers.

The use of fixed or random sampling points is a topic of much continuing debate. Geldreich (1996) reported that in a survey of 1,796 water supply utilities in the USA, about one third used only fixed sampling points, with 50% using a combination of random and fixed points. He recommended that some sampling locations be varied, so that all sections of the network are monitored over time. Burlingame and O'Donnell (1993) argue that the use of random taps increases the detection of water contaminated within households (which is outside the regulatory framework), since the water supplier has no control over consumers’ premises. Similarly Dufresne et al. (1997) have demonstrated that the number of positives and the number of samples collected can be reduced by selecting sampling points that were protected and well maintained. Similarly, a task group, appointed by United Kingdom Water Industry (1995), concluded that there were advantages in adopting a wholly fixed-point system. These included
the control and maintenance of the taps, greater compatibility of data and reduced cost. Other studies have indicated that the type of tap, particularly mixer taps, and material of construction may also influence water quality. These factors need to be considered in the design of a monitoring strategy. If random taps are to be used, it may be that identification of premises with suitable taps may be a more important consideration than achieving true randomness (Anon, 1994).

For statutory purposes, the location and number of sampling points may be stipulated within the appropriate regulations of that country. For example, the UK Water Supply Regulations stipulate that at least 50% of distribution samples must be taken from random locations (HMSO, 1989). For strategic monitoring, locations will be selected to gain the best practicable information about the area of the system being investigated. For this purpose, depending on the laboratory resources available, sampling locations may be more numerous than required to satisfy the regulations. Regardless of the reason for the monitoring it will have the common objective of providing sufficient information to allow the water quality in all service areas to be characterised.

6.4.3 Frequency of sampling

There is no absolute rationale for the frequency of sampling and adopted frequencies reflect the need to balance the benefits of better information arising from greater frequency with increasing costs (and decreasing returns) as overall frequency increases. The guidelines and regulations of individual countries generally prescribe the minimum sampling frequency to be achieved to meet statutory requirements. These sampling frequencies are usually based on the population served by the network/zone or, less frequently, on the volume of water supplied. For example in France, a minimum of 24 samples each year must be taken from distribution systems serving 10 000 – 20 000 inhabitants. In the Netherlands the frequency is similar, while the UK Regulations prescribe a more intensive programme of 48 samples per annum. In Germany the prescribed frequency is similar to that set for treatment works at one sample per 15 000 cubic metres of water supplied.

Although jurisdictions prescribe minimum sampling frequencies it is often necessary to collect additional samples to improve the overall picture of water quality in the distribution system. Supplementary samples should be collected at locations which, from historical data, are known to experience problems. Sampling frequency should also be increased following remedial actions, for example in response to boil water orders, or following interruptions in supply. In most cases a failure in terms of \textit{E. coli} or thermotolerant coliform detection
will initiate re-sampling, which may be followed by intensive investigations to identify the source and extent of the contamination. While re-sampling is commonly required the rationale underlying this (as a procedure prior to further investigation and action) is unclear. Given the known temporal and spatial variability of microbial water quality it is logical that re-sampling would often fail to detect continued contamination without indicating that the cause of the original contamination had been limited or controlled.

Some water suppliers carry out much more sampling within the distribution network than required to satisfy the regulations. Strategic monitoring programmes will be carried out to investigate specific problems such as high incidence of taste and odour events or the need for mains replacement or renovation. Each distribution system will have its own unique monitoring needs and the monitoring programme should be designed to address these using the available analytical resources. The impact of the timing of sampling should be recalled in interpreting results. Thus, for example, most sampling will be undertaken within the normal working week and may not detect changes arising from abnormal patterns of demand (such as football cup finals).

6.4.4 Volume of sample

The volume of sample collected must be sufficient to allow analysis at the limits of detection stipulated in regulations. For coliform bacteria this is 100 ml. Heterotrophic plate counts are usually expressed on a per ml basis. Given that samples may have to be re-analysed, the volume of sample will therefore generally be between 250 and 500 ml. In the Netherlands, coliform and \textit{E. coli} counts are expressed per 250 ml and so sample volumes will be greater to satisfy these requirements.

Demonstrating the absence of indicator microorganisms in 100 ml volumes, although adequate for statutory requirements, does not provide information about how close to compliance water quality is. For this reason some water suppliers routinely, or as part of special investigative studies, may collect and analyse sample volumes of between 1 and 10 litres. Volumes of this magnitude can be analysed by small modifications to existing analytical methods or by multiple analyses of 100 ml to 1 l volumes.

If microorganisms were distributed randomly in distribution systems, the use of the Poisson distribution would be appropriate in calculating the confidence limits for occurrence of indicator bacteria (Haas and Heller, 1986). However, it has been suggested by several workers (\textit{e.g.} Pipes \textit{et al.}, 1977;
Gale, 1996a) that the distribution of bacteria tends not to fit this pattern, instead they occur in clusters within a bulk supply. Gale (1996b) analysed the statistical distribution of confirmed coliform densities and total heterotrophic bacteria densities, using monitoring data from eight UK water companies. It was found that the log value of the bacterial density varied in an approximate linear fashion when plotted against the percentage of the data that was less than this value: this is known as a log-normal distribution. Extrapolation of the log-normal distribution of confirmed coliforms (1-9% of all samples) implied that where 100 ml samples were recorded as 0/100 ml, the actual concentration may have been as low as < 1/10^7 litres or as high as 1/litre. Similar clustering of a small proportion of high counts could be caused by sporadic contamination of the distribution system through, say, floc carryover and filter breakthrough (Gale, 1996b). Gale (1996b) concludes that ideally a model of the risk of exposure to pathogens would take account of the density of the organism in raw water, the removal efficiency by subsequent treatment processes, the variation in tendency to cluster and an estimate of water consumption.

In addition to providing some indication as to the true numbers of microbial indicators of faecal pollution in distribution, analysis of large volume samples increase the chance of detecting clusters or pulses of bacterial contamination particularly if taken over a period of time such as 30-60 minutes. An alternative to large volume grab samples is the collection of a composite sample. This is composed of a series of small volume samples collected at time intervals that are bulked together to form one large sample. Depending on available analytical resources analysis of individual samples would provide an indication of the bacterial distribution. It can be difficult to arrange for large volume or composite samples to be collected at randomly selected locations such as consumers’ taps, and it is best restricted to fixed sampling points.

6.4.5 Sample collection

Sampling for microbiological analyses requires care, with observation of the general principles of aseptic technique. All equipment used for sampling should be thoroughly cleaned and preferably sterilised before use. The sample containers should be sterile with wide mouths that are shielded from contamination. They should contain sufficient sterile reagent to neutralise any residual disinfectant in the water and samplers should be trained to ensure that thorough mixing occurs immediately after sampling.

For some purposes and especially in relation to the performance of the supply agency the sampling procedure used has to ensure that water from the main is collected and not the stagnant water in the supply pipe. For other
purposes (especially in relation to public health investigation) interest may focus on the water that has gone through typical processes of deterioration, as this is what consumers will be exposed to. Collecting mains water is usually achieved by running water to waste for a period of two-three minutes (Anon, 1994; APHA, AWWA, WEF, 1998), but given the differing lengths of service pipes this may not always be adequate. Other methods, such as running to waste until a constant temperature is reached (Anon, 1994), particle counts have stabilised (Burlingame and Choi, 1998) or (if appropriate) a chlorine residual is detected would appear to be more certain, but rather time consuming. After reviewing the results of studies on flushing Prévost et al. (1997) suggest a period of five-ten minutes may be necessary. However, the consumers whose taps are being used do not like these methods because they are perceived as being wasteful (or costly, if on a metered supply). The importance of this step in the sampling procedure cannot be over emphasised. Since water in the service pipe may reach relatively high temperatures, heterotrophs may grow to higher densities than in the water main (Geldreich, 1996). In addition, the high surface area to volume ratio of service pipes encourages the decay of chlorine residuals, again allowing a greater potential for bacterial growth. Without an adequate period of flushing a representative sample will not be obtained. However, not all workers agree with this. Prevost et al. (1997) demonstrated that although numbers of bacteria increased with distance from the treatment works, stagnation within the service pipe did not influence numbers appreciably. Similarly Kerneis et al. (1995) found that residence time had little influence on the heterotrophic plate count.

The introduction of new designs of taps (mixer), the use of plastics in construction and the provision of inserts as anti-splash devices has caused much discussion on the need for, and the best method of, sterilising taps prior to sampling. The traditional method of sterilisation is to heat the outside of the tap, in the direction of spout to base. Although this method is satisfactory where metal taps are used at premises controlled by the water supplier, they may be considered too hazardous at consumers premises. For sampling at these locations heat has almost completely been replaced by chemical methods of disinfection. Sodium hypochlorite is the most widely recommended chemical disinfectant. It is effective against a wide range of bacteria, including spores, and viruses. Only fresh solutions should be used as the concentration of chlorine decays with time. The consensus opinion on concentration is to use a 10% solution of household sodium hypochlorite for swabbing, or a 1% solution where a spray is used. It is essential that tap surfaces are clean before the use of a chlorine-based disinfectant since they react readily with all types of organic matter. In some cases isopropanol is used for tap disinfection as it is effective against some of the more resistant bacteria, such as mycobacteria, it is water miscible and evaporates at room temperature, leaving no residue. No particular
precautions other than simple tap flushing, have to be taken to ensure that the disinfectant does not contaminate the sample. In common with most chemical disinfectants, it precipitates proteins that may then form a protective layer for bacteria. The tap body and spout must therefore be clean before application. Isopropanol has the disadvantages that prolonged contact may result in skin irritation, swelling of rubber and hardening of some plastics. Burlingame and Choi (1998) suggest that the concentration used should be at least 70%, but a slightly lower concentration 60-70% is said by Gardner and Peel (1986) to be more effective.

6.5 Approaches to sampling in non-piped systems

In many areas where communities rely on non-piped supplies, resources to carry out routine bacteriological monitoring are very limited. This is often further complicated as most small water supplies are community-managed and therefore it is difficult to ensure that the “supplier” is able undertake an expected level of quality control monitoring and therefore there is greater reliance on external verification. Furthermore, enforcement of action is usually difficult as community-managed systems are often difficult to regulate directly and this becomes impossible when water hygiene is evaluated (Howard et al., 2001a). It is possible, however, to undertake programmes as described below. Given that monitoring microbial quality may be expensive, when considering the development of sampling programmes for point sources, it is essential that the monitoring programme is designed to meet a clearly defined management need and that the data derived will result in useful information (Bartram, 1999; Adriaanse, 1997; Ongley, 1998).

As for all water supplies, the use of sanitary inspection is extremely important as a means of assessing long-term risks and in analysing the causes of contamination when this is found. Sanitary inspections are visual assessments of the infrastructure and environment surrounding a water supply taking into account the condition, devices, and practices in the water supply system that pose an actual or potential danger to the health and well-being of the consumers (WHO, 1997). The most effective way to undertake sanitary inspections is to use a semi-quantitative standardised approach using logical questions and a simple scoring system. There exist a number of example forms that can be used (WHO, 1997). Sanitary inspections are complementary to water quality analysis and there is an increase in the power of subsequent analysis when both types of data are available.
6.5.1 Selection of methods and indicator organisms

For communities where point sources are commonly used, the use of on-site testing kits is often recommended given the large distances between the sources and laboratories and the very significant problems with sample deterioration (Bartram and Ballance, 1996). There appears to be no significant difference in the reliability of results obtained from such kits in comparison to laboratory testing providing the staff using them are properly trained and maintain an aseptic technique. Kits using MF, MPN and P/A methods are available.

Where bacteriological testing is undertaken using test kits, it is likely that *E. coli* or thermotolerant coliforms will be the indicator parameters analysed. However, for shallow groundwater, the use of faecal streptococci may provide more reliable results given their greater environmental resistance and because there is evidence that thermotolerant coliforms may multiply in nutrient enriched environmental waters (WHO, 1996; Byappanahalli and Fujioka, 1998). Studies in Uganda using sorbitol-fermenting bifido-bacteria, which are unique to human faeces showed a stronger relationship with faecal streptococci than thermotolerant coliforms (Howard *et al.*, 2001b). Most kits for thermotolerant coliform analysis can also be used for faecal streptococci analysis, although they must be able to sustain 48 hour incubation times.

6.5.2 Water quality sampling approaches

The degree to which sampling of point water sources is developed is dependent largely on the objectives of the monitoring programme being implemented. Very few countries have fully developed programmes of rural water supply testing. Indeed, although such approaches do provide an overall indication of water quality and its variation, it does not necessarily yield data from which management decisions can be easily made.

There are two main approaches (years-group approach and longitudinal study sample) that can be recommended for sampling of point water sources, which are outlined below. In addition, a brief section is included regarding assessment-only approaches, which are not recommended. The recommended approaches work on a slightly different basis and provide somewhat different information. Common to both approaches, however, is that a sample of water sources are tested during each sampling round.
The first stage in both approaches is to compile an inventory of all the water sources to be included in the monitoring programme (Lloyd and Bartram, 1991). A second key element in both approaches is to ensure that testing is timed to coincide with those times when water quality may be most threatened, usually during the wet season. However, it should be noted that some shallow groundwater systems show very rapid response to rainfall and this may need to be considered when designing the sampling programme (Barrett et al., 2000). Samples should be taken from the principal outlet – handpump, spring outlet or bucket used to take water from a well.

6.5.2.1 Year-groups approach

In this approach, all the water supplies are assigned to a particular “year-group” and a rolling programme of visits developed (Bartram, 1999). All the sources listed in each “year-group” would be visited, with the aim that all supplies would receive repeated visits over a time frame of between two to five years. On each visit, detailed surveys would be undertaken including sanitary inspection, water quality analysis and household visits made. Key to this approach is to ensure that stratified or cluster sampling approaches are adopted to ensure that supplies in different parts of the country were included within each ‘year group’. If this is not done, then the results from particular “year groups” may provide a distorted picture of the microbiological quality of water, as it may be biased because of technology type, hydrogeology or pollution loading specific to particular areas. The “year-group” approach provides the monitoring body a greater breadth of information as it attempts to cover all water sources. The data may also be used to identify actions required to improve water quality, although the restricted numbers of samples at sources may mean that it is more difficult to develop a full understanding of water quality variation.

6.5.2.2 Longitudinal study sample

In this approach, a representative sample of water supplies is visited on a regular basis. It is therefore different from the above approach in that it does not attempt to provide data on all sources within the country, but rather addresses developing a more in-depth understanding of the variation in quality of different types of water sources and different parts of the country. This can be used to assess whether microbial quality and risks vary over time and provides useful insight into how effective community operation and maintenance is and what improvements are required both in terms of training and design. The longitudinal study approach aim is to use the data from the sample to inform
overall implementation and management of the quality of water by ensuring that the most important factors in causing microbial contamination are identified and preventative and remedial actions developed. These apply beyond the sample of water sources included within the clusters and can form the basis of a broader national strategy for water quality improvement.

6.5.2.3 Assessment only approaches

In some countries, sampling of the water sources only occurs during the source selection stage and there are often particular levels of microbial contamination (usually defined on the basis of thermotolerant coliforms or more rarely *E.coli*) above which the source should not be used. A common value used is 50/100ml. However, such approaches have very limited use as the results of a single test may not provide a realistic estimate of the microbial quality of the water (particularly as this would not typically be done during worst case situations) and the use of an arbitrary figure of 50/100ml is unlikely to be meaningful in terms of health risk. Clearly, such approaches also fail to provide any indication of whether the protection works undertaken have been effective in reducing pollution and the designs used have rarely, if ever, been properly evaluated in terms of their ability to reduce contamination as expressed through log-reductions in bacterial densities.

Other countries either complement or replace the testing of sources during selection with a test on commissioning. This has the advantage that it provides a better indication of the quality of the supply, but again may not reflect seasonal variation in quality. Such approaches will also fail to address the greater concerns of water quality deterioration over time in supplies where operation and maintenance is weak.

6.5.4 Tanker trucks and vendors

These are treated separately as vending is a commercial practice and therefore more amenable to direct control than when water supplies are community-managed. Where trucks collect water from water supply utility hydrants, the routine testing of the quality of water in the trucks and at the hydrants should form part of the routine distribution testing by the water supplier. In the first instance an assessment should be carried out covering a sample of filling stations and tankers, followed by a lower-intensity routine monitoring programme when the day of sampling, selection of hydrants and selection of trucks vary in order to ensure to avoid biased results. This can be
linked to codes of sanitary practice both by the water supplier and the tanker trucks (Lloyd et al., 1991).

Where vendor supplies are not taken from utility piped supplies, routine testing and sanitary inspection is still desirable, although the type of vending may dictate the ease with which this is implemented. For tanker trucks, a rolling programme of random testing can be initiated, although it may be difficult to identify source waters. For very small vendors, it may not be possible to undertake routine monitoring, although occasional assessments would be worthwhile. In both cases, it is critical that the monitoring will lead to some form of action, whether this is through working with vendors to improve practices, regulating vending practices or banning all vending.

6.5.5 Household water

The testing of water stored in households is important to ascertain the quality of water actually being consumed. This is important because post-source deterioration in quality may have occurred and therefore good quality water at source may have become severely degraded by the time it is consumed and remedial actions (for instance hygiene education programme) may be required. The testing of household water is therefore an important component of an integrated risk-based approach to water quality.

Household samples should be taken from the drinking water storage vessel used by the family and containers used for collecting and transporting the water. A water chain can be tracked from source to storage with samples taken from source, collection vessel and water storage container. This often provides useful information regarding where and what type of interventions (educational, technical) are most appropriate. Generally, household testing programmes should be linked to source water testing programmes to ensure that the monitoring team understand whether poor quality in the home results from re-contamination or poor source water quality.

The numbers of samples and the selection of households will depend largely on the principal objective for the testing of household water. If the major purpose is to simply undertake random sampling of household water (which may be an important part of the monitoring programme whether “year group” or longitudinal study) then a stratified random sampling approach can be adopted. In this case, no specific intervention is being evaluated although the collection of information about sources and the type and cleanliness of the storage container may indicate where major problems lie.
This data can also be used to check on the use of feedback of surveillance results on household water quality. For instance in Uganda, the simple process of feedback of information and routine testing led to observable improvements in water quality stored within the home (Howard and Luyima, 2000). When such programmes are initiated it is important that different households are visited in each sampling period to prevent a bias developing due to repeated visits by surveillance staff. However, a cluster sampling approach may be adopted by identifying sentinel communities believed to be at greater risk because they have least access to direct connection or because they are more affected by interruption in supply.

In some cases there may be other specific objectives for testing water in the home. These may include evaluating the impact of a particular health education programme or household water storage and treatment interventions. In this case, a study would be designed to measure the impact between an intervention group and a control group thus allowing an evaluation of the impact of the intervention. Alternatively, the influence of the type of source, frequency and duration of discontinuity, or type of storage vessel on household water quality may be assessed in a community. In this case, a cluster sampling approach would typically be used to keep the number of households included to a reasonable number that allows intensive investigation.

6.6 Summary

This chapter provides a summary of possible sources of faecal contamination in drinking water and describes recognised sampling regimes in order to detect contamination. The small volume of samples collected during a reporting period represents only a tiny fraction of the total quantity of water delivered during that period. Thus, the challenge of sampling is to provide maximum information on water quality in the distribution system using the data from a limited number of samples. The ingress of faecal contamination into the distribution system should trigger immediate responses and this is covered in Chapter 7. The approaches available for sampling water quality from non-piped systems are also covered, with indications provided for actions to improve water quality.
REFERENCES


AWWA (1986) AWWA Standard for Disinfecting Water Mains. AWWA C651-86, Denver CO.


