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Risk management for distribution systems

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7.1 INTRODUCTION

The safety of drinking-water depends on a number of factors, including quality of source water, effectiveness of treatment and integrity of the distribution system that transports the water to consumers. At every stage in the production and delivery of drinking-water, hazards can potentially compromise the quality of the water. Piped distribution systems may be less vulnerable to contamination than open surface-water catchments; however, if piped systems become contaminated, there may be no treatment processes to reduce risks from the introduced hazards.

The previous chapters have reviewed knowledge about the presence, growth and significance of microorganisms in piped networks. They have also

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described the operating practices of water supply organizations that can directly or indirectly influence the presence of microorganisms, especially those of significance to public health. However, this information is of little benefit unless it is part of a package of working practices designed to manage hazards in the whole supply system. Identifying, prioritizing and preventing risk arising from such hazards is the basis of a water safety plan approach. Such an approach is described in Chapter 4 of the latest edition of the World Health Organization's (WHO) *Guidelines for Drinking-Water Quality* (WHO, 2004). The remainder of this chapter demonstrates how control measures for distribution system can fit within a water safety plan.

7.2 WATER SAFETY PLANS

7.2.1 Elements of a water safety plan

Figure 7.1 describes development of a water safety plan. The objective of the plan is to supply water of a quality that will allow health-based targets to be met. The success of the plan is assessed through surveillance. The three central components of a water safety plan are:

- system assessment, which involves assessing the capability of the drinking-water supply chain (up to the point of consumption) to deliver water of a quality that meets the identified targets, and assessing design criteria for new systems
- identification of control measures in a drinking-water system that will collectively control identified risks and ensure that health-based targets are met (for each control measure identified, an appropriate means of monitoring should be defined that will ensure that any deviation from required performance is rapidly detected in a timely manner)
- management plans that describe actions to be taken during normal operation or extreme and incident conditions, and that document system assessment (including upgrade and improvement), monitoring, communication plans and supporting programmes.

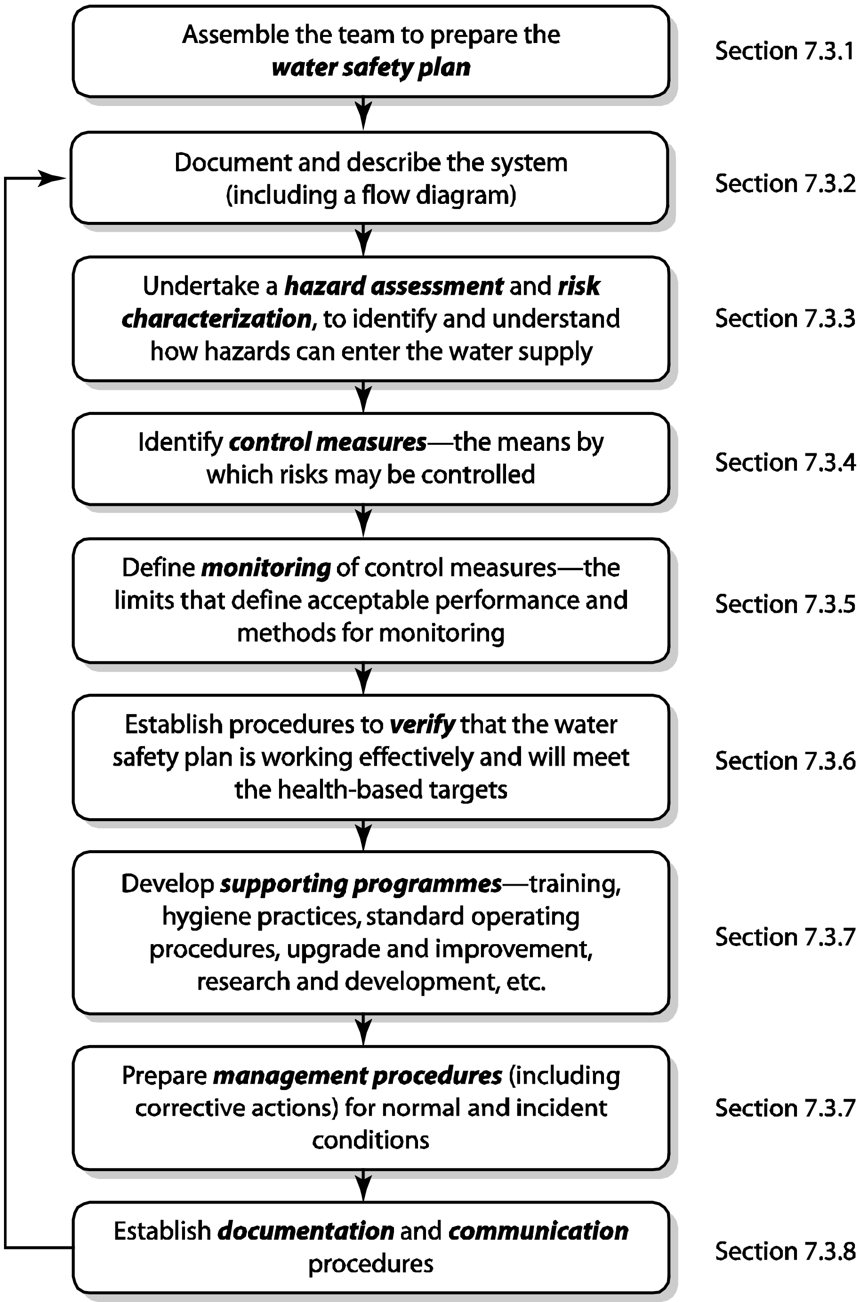

Figure 7.1. Overview of the water safety plan framework.

7.3 WATER SAFETY PLANS FOR DISTRIBUTION SYSTEMS

In general, water entering a drinking-water distribution system should be safe to drink, without additional treatment, once it has reached the first consumer connection. Therefore, the management of distribution systems primarily involves maintaining water quality, and minimizing the risk of contamination and deterioration of quality during transport. However, many distribution systems are a complex array of pipes, pumps, tanks and valves, which means that risks are not always as easily identified as in other areas of drinking-water supply.

7.3.1 Assemble team

The first step in developing a water safety plan is to assemble a multidisciplinary team with an understanding of the specific distribution system, to describe that system. The team would typically include managers, engineers (operations, maintenance, design and capital investment), water quality control staff (microbiologists and chemists) and technical staff involved in day-to-day operations. All members of the team should have a good knowledge of the system.

7.3.2 Document and describe the system

The next step is to document and describe the system. The description can include a basic flow diagram of the drinking-water distribution system, and reference to maps showing water quality networks and zones. It is important to capture the elements of the water supply system in sufficient detail to allow risks to be assessed and control measures to be identified. Therefore, pressure, pumps, connections, valves (and their status) and tanks need to be considered. Exmples of important features include:

- service reservoirs, balancing tanks, booster stations and (when used) break-pressure tanks
- zones of supply from each source
- layout of primary, secondary and tertiary pipelines (coded by colour or numerically)
- location of major valve boxes and junctions
- flow within the system (clearly indicated, noting where there are areas of interconnection between different zones)
- numbers of consumer connections
- hydraulic system flow rates and paths (including two-way flow)
- connections with high backflow hazard.

The representation of the system must be conceptually accurate, because the team will use the diagram as the basis for hazard analysis. If the flow diagram and system maps are incorrect, the team may miss potentially significant hazards, and may fail to identify existing or required control measures. Therefore, the team should validate the completeness and accuracy of the flow diagram and maps; for example, by visually checking against features observed on the ground. Proof of validation is typically recorded, together with an accountability (e.g. a member of the team may sign and date a flowchart and a set of maps to validate that they are accurate and complete).

The example given in Box 7.1 (below) illustrates the importance of being aware of the major components of the distribution system.

7.3.3 Hazard assessment and risk characterization

Managing risks in distribution systems poses different challenges to managing risks in, for example, a treatment plant. When considering engineered treatment processes such as filtration and disinfection, the emphasis is on selecting and controlling processes that will reduce risk to an acceptable level, assuming that the source water has potentially unacceptable contamination. When considering distribution systems, the focus is on preventing recontamination or degradation of water quality caused by breaches in system integrity or difficult operational circumstances. In both situations, it is useful to determine what contaminants are of concern (hazard assessment), and how they may reach unacceptable levels (risk characterization). This makes it easier to identify important potential contaminants (hazards) and the risk of events occurring that could cause these hazards to contaminate the system (hazardous events).

Risk management in distribution systems is similar to that in catchments, in that the aim is to prevent the introduction of hazards. However, a major difference is that distribution systems represent the final barrier before consumption in many supplies, whereas hazards arising in catchments may be reduced during storage and treatment.

In risk assessment, it is important to be explicit about the risks that are to be assessed, in terms of who is at risk, and what they are at risk from. Therefore, the following questions are helpful as a first step in risk assessment:

- How is the water to be used and what exposure routes are relevant?
- What consumer education is in place for water use?
- How are consumers notified of potential contamination?
- Who is the water intended for?
- What special considerations are in place for vulnerable groups such as infants, the elderly and the immunocompromised?

Box 7.1. Outbreak of Norwalk virus caused by a cross connection between a municipal supply and a private supply.

During one week in August 1980, approximately 1500 people from a small community in the north of the State of Georgia, USA, developed gastroenteritis. Stool culture was negative for *Salmonella*, *Shigella* and *Campylobacter*. Only four stool samples were examined by electron microscopy and these were negative. However, 12 of 19 paired sera showed a fourfold rise in titre of antibody to norovirus, confirming the diagnosis. A door-to-door survey of households revealed marked variation in reported attack rates, with the highest attack rate (68%) in people living close to a textile plant. Epidemiological investigation also found an association between illness and consumption of tap water.

Within the affected area there were two water supplies — a nearby river and a spring source. There was no relevant illness in people whose water was supplied from the river source; those who were affected by the outbreak had received water sourced from the spring

The spring source, which was chlorinated, was found be satisfactory and the chlorination plant to be working adequately. There were, however, two known connections between this municipal water system and a private system supplying water to a textile plant. The water for the textile plant came from five wells and two springs in the area. Each source was chlorinated, though the chlorination equipment was antiquated and inadequate. One of the springs was contaminated with high counts of total and thermotolerant coliforms, and storage reservoirs for the textile plant water were grossly contaminated with algae and pinnate diatoms.

The water pressure in the municipal system (110 psi) was normally higher than in the textile plant system (100 psi). However, demands on the municipal system sometimes reduced the pressure to only 80 psi, which would have allowed substantial flow of water from the textile plant system to the municipal system.

The outbreak illustrates the importance of avoiding cross connections between systems where the water utility does not have complete control of the water quality of both systems.

Source: Kaplan et al. (1982).

Desktop risk assessment

The next step in risk assessment is to systematically evaluate the system's potential vulnerability to external hazards, using the flow diagrams and system maps. The initial evaluation is desk-based and relies on data supplied by design and operational staff.

Information that would normally be part of this assessment includes the following:

- areas where (possibly seasonal) soil moisture content or flooding makes it likely that faecal matter from sources on the surface or shallow subsurface will enter the system
- any other sources of faecal matter found in the urban area (e.g. animal husbandry)
- areas of high population density (used as a surrogate for faecal loading in the environment)
- areas of low pressure within the system
- areas of intermittent supply and their likely recharging pattern
- pipe material, age and condition (a vulnerability score can be developed based on likely risk of breaks or joint failure)
- cross-connections, proximity to sewers and high-hazard facilities, and the relative depth of water supply pipes and sewers
- low-lying areas prone to flooding
- depth to which pipes are buried (this differs from the point above concerning sewers, because it relates to the risk of accidental breakage by traffic, etc)
- condition and age of service reservoirs
- areas where there are significant numbers of illegal connections or where the tertiary infrastructure has been installed by nonutility staff and quality of construction is uncertain
- areas where a significant proportion of houses use household storage, which may include the attachment of small pumps to the main, for pumping to roof tanks
- areas of known high leakage
- large buildings, such as hospitals.

At each step, the objective is to identify how contamination could arise from the identified hazards, by considering the events that could lead to the presence of contamination. The output from this exercise is a list of hazardous events, their associated hazards and a reference to where in the system or process the risks are located.

Sanitary survey

The above steps provide an overall picture of the distribution system and a framework for identifying hazardous environments and vulnerability. The next step is to carry out a field assessment of the system, to identify potential hazards and hazardous events, and the existence of possible control measures (described in Section 7.3.4).

The sanitary survey gathers field evidence to support the risk assessment. It involves systematic investigation of the complete distribution system, to identify all major hazards and vulnerable points. The survey deals mainly with the physical state of infrastructure, focusing primarily on external threats.

In undertaking a sanitary survey, standard forms can be used for major structures of the same type, such as service reservoirs, major valve boxes, road or culvert crossings and distribution infrastructure. Standardized forms for sanitary surveys and inspections are available (WHO, 1997; Howard, 2002), and can help to ensure that the importance of different major components of the system is evaluated, and persistent failures identified.

Urban piped water supplies can be difficult to survey, because most sanitary inspections are based on observation. Leaks associated with deep-laid pipes are often difficult to detect through observation, and contamination may occur a significant distance from a sample site. However, simple visual and question-based approaches can still provide useful information about whether risks are at the level of the general supply or are localized. Thus, questions on the inspection form should deal both with risks found in the immediate area and those that relate to broader supply problems. Local risks will include aspects such as the pooling of stagnant water around the joints between riser pipes and delivery mains. Tap leakage, pipe exposure and waste allowed to collect around the tap may be significant causes of contamination. Inspections are required at service reservoirs because these have the potential to cause widespread contamination.

There are difficulties of scale in a comprehensive sanitary inspection of an entire urban piped water system. The areas to be inspected by field staff should be broken down into segments that can be easily covered within one day — this may be a full water supply zone or an acceptable subdivision.

The importance of having an understanding of the vulnerability of a distribution system is illustrated by the example given in Box 7.2 (below).

Prioritizing risks

In large and complex systems, so many risks may be identified that it is difficult to set priorities. Simple matrices for risk assessment typically combine technical information from guidelines, scientific literature and industry practice with well-informed "expert" judgement, supported by third-party peer review or benchmarking. The risk ranking will be specific for any particular water supply system because each system is unique.

Box 7.2 Cryptosporidiosis associated with contamination of a water conduit.

During August and September 2000, there were 168 laboratory confirmed case of cryptosporidiosis in residents of Belfast. Of these cases, 117 lived within the area supplied by a single water conduit. This drinking-water conduit had been built 110 years earlier. It was seven miles long and supplied drinking-water to some 216 000 people. The water passing through the conduit came from a water treatment works and was not further treated before being supplied to a number of distribution reservoirs and then consumers.

Initial sampling of the water was negative for *Cryptosporidium* oocysts, although several large-volume samples taken from the service reservoirs were positive, with counts of up to 2.2 oocysts per 10 litres. To further investigate the integrity of the conduit, chlorination was turned off at the water treatment works and samples for total coliforms and *E. coli* taken at various points of the conduit through pre-existing airwells. Counts of total coliforms and *E. coli* increased substantially between two sampling points. Close-circuit television (CCTV) cameras were put into the conduit between these points. CCTV demonstrated black staining of the roof of the conduit, which was subsequently shown to coincide with the location of a private septic tank. On further inspection it was found that the outer brick wall of the conduit had been removed to enable the outflow of the septic tank to be constructed. Consequently, the overflow from the septic tank could contaminate the drinking-water distribution system after the treatment stage.

Source: Department of Public Health Medicine(2001).

By using a semiquantitative risk assessment, the water safety plan team can calculate a priority score for each hazardous event identified. The objective is to focus on the most significant hazards and hazardous events, to begin to identify what might be the most important control measures (Section 7.3.4). Several approaches to ranking risk are available, and the team needs to determine which approach it will use. An example of an approach is given in Table 7.1, where the risk score for a particular hazardous event is determined by combining the likelihood of its occurrence with the severity of the consequences.

Table 7.2 gives examples of descriptors that coulc be used to rate the likelihood and severity for calculation of the risk score; other descriptors might be more appropriate in some situations.

In developing a water safety plan, it is possible to adopt an approach of continuous improvement, taking more risks into consideration at each iteration of the plan. To do this, the team needs to determine a cut-off point to distinguish between hazards that require immediate attention and those that can be considered in future iterations.

Table 7.1. Example of a simple risk scoring table for prioritizing risks.

	Severity of consequences				
	Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood					
Almost certain	5	10	15	20	25
Likely	4	8	12	16	20
Moderate	3	6	9	12	15
Unlikely	2	4	6	8	10
Rare	1	2	3	4	5

Source: Davison et al. (2002)

Table 7.2. Examples of definitions of likelihood and severity categories for risk scoring.

Item	Definition	Weighting
Likelihood		
Almost certain	Once a day	5
Likely	Once per week	4
Moderate	Once per month	3
Unlikely	Once per year	2
Rare	Once every 5 years	1
Severity		
Catastrophic	Potentially lethal to large population	5
Major	Potentially lethal to small population	4
Moderate	Potentially harmful to large population	3
Minor	Potentially harmful to small population	2
Insignificant	No impact or not detectable	1

7.3.4 Control measures

In the context of a water safety plan, a control measure is any action or activity that can be used to prevent or eliminate a hazard, or reduce it to an acceptable level. Therefore, any risk management activity in a drinking-water supply is considered to be a control measure. Examples of control measures in water distribution are positive pressure, intact pipe networks, backflow preventers and vermin proofing on tanks.

Control measures are identified by considering the events that can cause contamination of water, both directly and indirectly, and the activities that can mitigate the risks from those events. Examples of control measures in the distribution system include:

- maintenance of the distribution system

- availability of backup systems (e.g. power supply)
- maintenance of an adequate disinfectant residual
- presence of devices to prevent cross-connection and backflow
- use of fully enclosed distribution system and storages
- maintenance of a disinfection residual
- appropriate repair procedures, including disinfection of water mains after repairs
- maintenance of adequate system pressure
- maintenance of security to prevent sabotage, illegal tapping and tampering.

In identifying control measures, operational criteria to differentiate acceptable from unacceptable performance are required. These criteria, referred to as "operational limits", are control measure variables that can be measured (either directly or indirectly) or factors that can be observed. Examples of measurable variables include minimum and maximum values for pH, chlorine residuals or hydraulic system pressure at strategic locations in the distribution system; an example of a factor that can be observed is the apparent integrity of vermin-proofing screens on reservoirs. Current knowledge and expertise (including industry standards and technical data), and locally derived historical data can be used as a guide when determining the limits. Ideally, operational limits have the following properties:

- they can be defined and monitored (either directly, or indirectly through surrogates)
- a predetermined response (i.e. a corrective action, described in Section 7.3.5) can be implemented when monitoring indicates that conditions have deviated from set limits
- the corrective action will protect water safety by either bringing the control measure back within acceptable limits or causing additional control measures to be implemented
- the process of detecting deviation from limits and of responding will be sufficiently rapid to maintain water safety.

Control measures that cannot be defined, but meet the other requirements listed above, can still be important and can form part of the water safety plan.

7.3.5 Monitoring to support risk management

There are three kinds of monitoring in the management of distribution systems — operational, process validation and verification — each of which has a different purpose, as shown in Table 7.3. This section considers operational monitoring; Section 7.3.6 looks at monitoring for process validation and verification.

Table 7.3. Types of monitoring in the management of distribution systems

Monitoring type	Purpose
Operational	Support management of the operation of the system, to ensure safety and to ensure that control measures are working effectively
Process validation	Demonstrate that control measures are capable of achieving the required outcomes
Verification	A final check that the entire water supply system is functioning correctly

Operational monitoring and selection of operational control parameters

Operational monitoring involves conducting a planned sequence of observations or measurements, designed to assess whether the control measures applied at a point in the system are achieving their objectives. Effective monitoring relies on establishing what will be monitored, how, when and by whom. In most cases, routine operational monitoring will be based on simple surrogate observations or tests, such as turbidity or structural integrity, rather than complex microbial or chemical tests (which are likely to form part of process validation and verification, Section 7.3.6).

An essential requirement of operational monitoring is the ability to assess performance of the system in a timely manner, and judge whether a control measure is functioning properly. Microbial parameters (e.g. indicator bacteria) are of limited use for this purpose, because the time taken to process and analyse water samples is too slow (although changes in heterotrophic plate counts can be used to monitor the effectiveness of control measures for limiting biofilm activity or maintaining system integrity). Generally, operational monitoring for control measures such as pressure and levels can be online and in real time, although this is not always essential.

If monitoring shows that an operational or critical limit has been exceeded, then there is the potential for water to be, or to become, unsafe. The objective is to monitor control measures according to a statistically valid sampling plan and in a timely manner, to prevent the supply of any potentially unsafe water. A permanent record of monitoring should be maintained. For example, if chlorine disinfection is being used as a control measure for a distribution system, the parameters monitored could be chlorine residuals, established for the given system at particular set points (generally in parts per million, ppm). A range of values would be included, again calculated for the system, outside of which an alarm would be set to sound via a telemetry system. Since pH and turbidity are integral to chlorine efficacy, these parameters might also be monitored. Should the telemetry system show that the disinfection control measure was not within acceptable bounds, a pager system could be used to alert water quality personnel. These staff would then take predetermined corrective actions to investigate the deviation and bring the water back into specification, as discussed in the next section.

Establish corrective action for deviations that may occur

A corrective action is the action to be taken when the results of monitoring at a control point indicate a loss of control. For example, the ability to change temporarily to alternative water sources is one of the most useful corrective actions, although this option is not always available. Corrective actions should be specific and predetermined where possible, so that they can be employed rapidly. To allow for unforeseen events for which there may be no predetermined corrective action, a general incident and emergency response plan should be developed, to at least set up a response framework. By ensuring that a contingency is available in the event of an operational limit being exceeded, safety of supply can be maintained.

The following are examples of possible corrective actions that could be taken when online monitoring of chlorine disinfection fails to comply with operational limits (all of these corrective actions would include action from the on-call or designated water quality personnel):

- ensure that the telemetry system is working and that the alarm is not false
- review or adjust the range of chlorine residuals, and increase the chlorine dosing level if necessary
- flush any undisinfected water from the main
- make any necessary repairs or operational control changes.

Communication is a crucial component of corrective actions. Therefore, a procedure for notifying sensitive customers (e.g. hospitals) and authorities (e.g. health departments) should be included in corrective actions. For example, it may be necessary to have an understanding with a local bottled water company, to ensure that residential customers at least receive drinking water in the event of a distribution system failure.

7.3.6 Verification

Verification is the final check of water safety. It provides an objective confirmation of the overall safety of the system. For example, biophysical verification activities, such as microbial and chemical monitoring, are likely to be undertaken in the distribution system. Verification also encompasses audit and review of the water safety plan, including checking compliance with operational procedures.

Verification monitoring involves using methods, procedures or tests, in addition to, and independent of, those used in operational monitoring, to determine whether the water safety plan:

- complies with the stated objectives outlined in the water quality targets
- needs modification and revalidation
- is controlling the identified hazard.

Verification monitoring may be less frequent than operational monitoring. For example, operational monitoring might be online (and thus continuous) through a telemetry system, whereas verification monitoring of distribution storage tanks and reservoirs might be carried out fortnightly.

Bacterial indicators, such as *E. coli*, are the indicator most frequently used for final verification of microbiological quality. Although microbial monitoring can be used in verification as a final check, end-point testing should not be relied on for operational control because, by the time samples have been processed and analysed, water will already have been treated and delivered to consumers.

Auditing of compliance with the water safety plan is another form of verification. The objective is to assess the extent to which the plan is being followed in practice. Auditing may involve both internal and external auditors, and may include review of important activities related to water safety, such as compliance with operational procedures, adoption of training plans and timely calibration of equipment. An example of a verification schedule is given in Table 7.4.

Table 7.4. Example of verification schedule for calibration of equipment.

Activity	Description	Frequency	Person responsible	Records
Calibration of equipment	Analysing and testing equipment to be maintained and calibrated according to maintenance schedules	According to maintenance schedules	Laboratory technician, operators	Laboratory calibration records

Process validation

Process validation involves obtaining evidence that the elements of the water safety plan will be effective. An example of such validation is the provision of objective evidence that a control measure, operating within its operational limits, will control the relevant hazard. Validation can be based on a variety of sources, including the scientific literature, trade associations, regulation and legislation, historical data, professional bodies and suppliers.

System-specific validation is essential, because variations in water or system design may have a large impact on the efficacy of certain control measures. Thus, a control measure that works in one distribution system may be less effective in another type of distribution system. Examples of process validation are:

- modelling of flow paths in storage tanks to validate the extent of mixing
- measurement of conditions for effective disinfection in storage tanks
- measurement of microbial parameters, such as heterotrophic bacteria and coliforms (in this situation, the lag time for return of results from culture-based methods can be tolerated, because this type of monitoring is not used to support the day-to-day management of water safety).

The water safety plan should be reviewed at predetermined periods to incorporate new information as it becomes available, and to ensure that the plan is still capable of controlling the identified hazards.

7.3.7 Supporting programmes and management procedures

The delivery of safe water through a water safety plan involves managing people and processes. Therefore, adequate supporting programmes, such as training, supplier quality assurance and good hygiene practices, are an important part of the plan. Supporting programmes are activities that are essential for effective operation of control measures and that indirectly support water safety. Actions required to operate the system according to the water safety plan need to be captured in the form of management procedures, such as standard operating procedures. Management procedures should be developed for both routine and incident and emergency conditions.

7.3.8 Documentation

Records are essential for reviewing the adequacy and implementation of the water safety plan. Four types of records can be kept:

- support documentation for development of the water safety plan
- records generated by the water safety plan system
- documentation of methods and procedures used
- records of employee training programmes.

Records demonstrating adherence to the water safety plan are needed to support the verification auditing activities. In the short term, tracking of records allows an operator or manager to become aware that a process is approaching its operational limits, and review of records can help to identify trends so that operational adjustments can be made. In the long term, periodical review of records allows trends to be noted, so that appropriate actions can be determined and implemented, to ensure continual improvement.

Documentation is an essential part of following the water safety plan; it is also a powerful way of demonstrating that all due diligence and reasonable precautions have been taken by the utility, because the information is readily available, readily trackable and transparent.

7.5 SUMMARY OF WATER SAFETY PLAN CONTENT

Table 7.5 summarises the suitable content of a water safety plan, with the elements categorised as "must contain", "should contain" or "may contain".

Table 7.5. Summary of requirements of a water safety plan.

Must contain:

- process flow diagrams and maps, including identifying control measures
- hazard identification
- water safety plan document
- identification of water safety plan team
- description of the water supply, intended use and vulnerability
- documented contingency plans.

Should contain:

- supplier agreement documents
- detailed specifications for chemicals and materials used in the water supply
- job descriptions for those holding principal accountabilities for operating the water distribution system
- corrective action plans for deviations
- record-keeping procedures
- validation data
- procedures for verification and revision
- documented incident procedure.

May contain:

- relevant manuals such as for line hygiene, preventative maintenance, and equipment calibration measurements
- job descriptions and accountabilities for all staff
- training programme and records for all staff
- findings and corrective actions from previous audits (including verification procedures)
- consumer complaint policy and procedure.

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