6

Process control

To assure optimal finished water quality, control programs should be comprehensive, and should include multiple barriers and adequate process design and operation. As discussed in Chapter 1, the third edition of the World Health Organization's (WHO) *Guidelines for Drinking-water Quality* provides guidance on the development of a water safety plan, based on a water safety framework (WHO, 2004). Such control programs are the basis for maintaining reliable treatment performance. Multiple barriers should provide a consistent level of protection, and adequate design and operation should ensure that performance meets specifications. Even so, treatment performance is likely to vary, mainly because of the dynamic nature of each individual treatment process, the interrelationship between different processes and changes in raw water quality, as discussed in Chapter 5.

This chapter looks at process control, in the context of a risk management approach, from source water to the distribution system.

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6.1 RISK ASSESSMENT AND PROCESS CONTROL

Use of risk assessment techniques as a tool for process control in the water industry has received increased attention in the past decade. Examples of such techniques include “hazard analysis critical control point” (HACCP) and “failure mode and effects analysis” (FMEA) (Hall, Watts & Egerton, 2000). In FMEA, risk is quantified (ranked) in terms of the frequency of specific failure events and the consequences of those failures, as illustrated in Table 6.1. Selection of appropriate failure events, such as a high concentration of particles or coliforms, is directly correlated with microbial risk. Using the rankings, risk can be quantified for individual elements of the treatment process or for whole treatment works.

Table 6.1 Example of ranking of frequencies and consequences for failure mode and effects analysis

Rank	Frequency of failure
1	Very unlikely (< 1/100 years)
2	Unlikely (> 1/100 years)
3	Moderate (> 1/10 years)
4	Frequent (> 1/year)
5	Very frequent (>1/month)
Rank	Consequence of failure
1	No impact on operation (increased operator effort only)
2	Limited impact (minor deterioration in output quality, internal incident report)
3	Moderate (customer awareness, increased pressure group activity)
4	Severe (regulatory exceedance, adverse publicity)
5	Catastrophic (life or health threatening, environmental damage)

Source: Hall, Watts & Egerton, 2000.

The water safety plan described in the WHO *Guidelines for Drinking-water Quality* (WHO, 2004) provides a common framework for applying risk management techniques in the water industry. The procedure has three main components:

- *System assessment* to determine whether the drinking-water supply chain as a whole (up to the point of consumption) can deliver water of a quality that meets identified targets. It includes assessment of design criteria for new systems.
- Identification of control measures in a drinking-water system that will collectively control identified risks and ensure that the health-based targets are met. For each control measure identified, an appropriate means of

monitoring should be defined, to ensure that any deviation from required performance is rapidly detected.
- *Management* plans describing actions to be taken during normal operation or incident conditions, and documenting the system assessment (including upgrade and improvement), monitoring and communication plans, and supporting programmes.

This common framework quantifies hazards or risks within the whole treatment process, and identifies important monitoring and remedial actions at designated hazard control points. The rest of this chapter discusses hazard control process in a conventional water treatment plant.

6.2 SOURCE WATER PROTECTION

Table 6.2 summarizes the main elements of a hazard control strategy for source waters. Understanding variations in raw water quality is important because such variations affect the treatment efficiency (as discussed in Chapter 5, Section 5.4) and thus the health risk associated with the finished water. In general, raw water quality is influenced by both natural and human factors. Important natural factors include wildlife, climate, topography, geology and vegetation. For example, beavers and other mammals are potential sources of *Giardia intestinalis*, and migratory geese have caused seasonal increases in coliform bacteria in some north-eastern water supply watersheds in the USA (Robbins et al., 1991). Human factors include point sources (e.g. discharges of municipal wastewater and industrial wastewater) and nonpoint sources (e.g. urban runoff, livestock or recreational activities). Municipal wastewater can be a major source of microbial pathogens, urban runoff and livestock can contribute a substantial load of coliform bacteria, and recreational activities involving body contact can be a source of faecal contamination.

Table 6.2 Hazard control elements for source waters

Potential control strategies	Control measures
Assessment of pollution sources	Wildlife Agriculture Sewage treatment plants
Watershed protection	Land acquisition, riparian barriers Land or water use restrictions
Hydrological conditions	Rainfall, flow, monitoring Changes in source water quality Reservoir destratification
Watershed networks	Reporting network Identification and prosecution of violators

Protection of source water can help to minimize microbial risk associated with the water entering a drinking-water treatment plant. Possible control measures to protect source water include land acquisition, watershed inspection programmes, reservoir-use restrictions and riparian buffers. Few water utilities own all or even most of the land within their watersheds; thus, it may be difficult for water utilities alone to control or reduce the risk from identified hazards. Competition for water and pressure for increased development in a catchment may appear to limit the extent to which potentially polluting activities can be reduced. However, it is often possible to contain hazards without substantially restricting activities. Collaboration between stakeholders can allow pollution to be reduced without reducing beneficial development.

From a water utility perspective, developing a monitoring programme and carrying out corresponding actions at the early stage of the treatment process are sometimes the most effective ways to minimize microbial risk from raw water. Examples of methods to reduce the risk include determining the vulnerability of the intake to microbial contaminants, managing the raw water pumping schedule and applying pretreatment oxidants.

Hydrological events can increase microbial levels in source water. For example, rainfall can wash microbes into receiving streams and increased stream flow can resuspend microbes settled in streambed sediments. Figure 6.1 demonstrates a peak in *Cryptosporidium* levels associated with rainfall, and subsequent increases in river flow and turbidity levels (Atherholt et al., 1998). Similar increases in total coliforms, faecal coliforms, faecal streptococci and staphylococci have been seen in other studies (e.g. Davis, Casserly & Moore, 1977). Changes in flow may also be due to release of water from upstream dams, reservoirs or other impoundments. Turnover of lakes and reservoirs following seasonal stratification can release microbes or other factors that increase disinfectant demand, which may interfere with treatment operations.

A watershed-monitoring network can be useful for detecting contamination events and alerting downstream users of the pending plume. For example, the Ohio River Valley Water Sanitation Commission (ORSANCO[1]) is a network of users of water from the Ohio River. ORSANCO monitors daily for a variety of contaminants, and serves as a centralized clearing house for data analysis and interpretation. By pinpointing the source of the contamination, violators can be identified and prosecuted. The result is a greater attention to minimizing contamination reaching the river and an overall improvement in water quality. Similar networks are present for some of the major rivers in Europe and Asia (e.g. the Rhine River in Germany, Holland and Switzerland; the Llobregat River in Spain; and the River Han in Korea) (Grayman, Deininger & Males, 2000).

6.3 COAGULATION, FLOCCULATION AND CLARIFICATION

Coagulation

Chemical coagulation pretreatment is the most important factor in ensuring efficient removal of microbes by coagulation, flocculation and clarification and by granular media filtration. It also indirectly affects the efficiency of the disinfection process. Although the coagulation process itself is unlikely to cause any microbial hazard or risk to finished water, a failure or inefficiency in the coagulation process could result in a high microbial risk to drinking-water consumers. Hazard control strategies for the coagulation process are outlined in Table 6.3.

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[1] www.orsanco.org

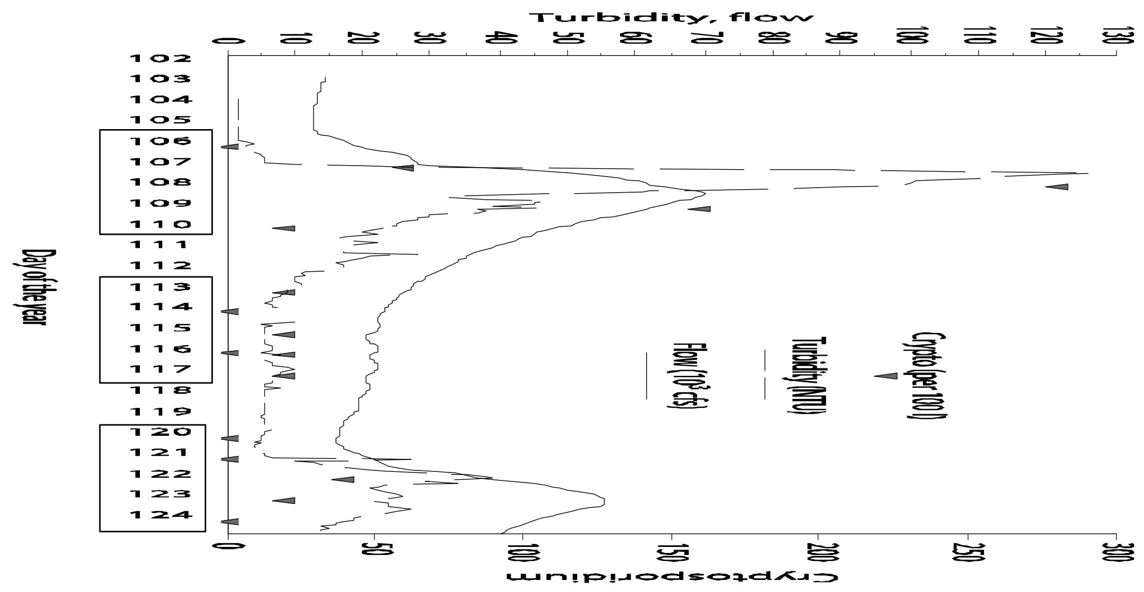

Figure 6.1 Hydrological event showing increases in *Cryptosporidium* oocyst levels accompanying increases in source water turbidity and river flow rate (Atherholt et al., 1998).

Table 6.3 Hazard control elements for coagulation, flocculation and clarification

Potential control strategies	Control measures
Chemical coagulation	Selection of appropriate primary coagulant and coagulant aid (if required) Dose (determined by testing) Coagulant feed paced to flow rate pH and alkalinity adjustment Appropriate mixing Temperature
Flocculation	Gentle mixing to maximize flocculation Flow rate Flocculant aids
Clarification	Surface loading rate Effective sludge removal Settled water turbidity or other process indicator

The first step is to choose an appropriate coagulant (and coagulant aid if necessary) and dose. Next, it is important to ensure that the chemical feed rate is appropriate for the plant flow, because changes in flow rate could result in an over or under-dose of coagulant, impairing performance. Water chemistry and temperature can affect the performance of many coagulants, and adjustment of pH may be necessary for optimal performance.

Commonly used approaches for determining appropriate coagulation chemistry and for monitoring coagulation include jar tests, streaming current detectors, zeta potential, pilot filters, historical dosage charts, visual observations, pH, alkalinity, temperature and ultraviolet (UV) absorbance (for a review, see Logsdon, Hess & Chipps, 2000). Typically, coagulation efficiency is evaluated using one or more of these approaches and the process parameters adjusted accordingly. The choice of approach depends on the site. For example, streaming current potential may be appropriate when charge neutralization is the main destabilization mechanism, but may not be suitable when enmeshment in a precipitate (sweep-floc) is the main mechanism.

Flocculation

Critical to the performance of effective flocculation is gentle mixing to promote particle aggregation. The calculation of the velocity gradient necessary for proper flocculation can be estimated by the G value, as shown below:

$$G = \left(\frac{P}{V\mu}\right)^{1/2}$$

where:
P = the power input to the fluid
V = the volume of the flocculator
μ = the absolute viscosity of the water

If the G value is too high, the floc may be sheared; if it is too low, sedimentation may occur within the flocculation basin. In water treatment, typical G values are 10–100/sec (Weber 1972). Although this calculation has many flaws, it is useful for flocculator design and scale-up (Letterman, Amirtharajah & O'Melia, 1999).

Clarification

Factors influencing clarification performance include the surface loading rate (expressed as flow rate per unit surface area of the clarification basin), the size and shape of the tank, flow velocity, adequate sludge removal and physicochemical characteristics of the water (USEPA, 1991; Gregory, Zabel & Edzwald, 1999). Recommended surface loading rates vary widely, depending on the type of clarification process. Conventional sedimentation basins may have surface loading rates of 0.6–2.0 m/h (0.25–0.8 gpm/ft^2). High-rate clarifiers may have surface loading rates of 7 m/h (2.9 gpm/ft^2) or greater. Adequate sludge removal is important because sludge accumulation reduces the volume of the clarification basin and can increase the velocity of the flow through the basin. To prevent the formation of currents and breakage of floc, the overflow rate should be as low as possible. Adjustable V-notched weirs provide operational flexibility.

6.4 FILTRATION

Granular media filtration is an important barrier to microbes (see Chapter 2, Section 2.5). It may be the only barrier in some cases; for example, for removing *Cryptosporidium* oocysts by direct filtration when chlorine is used as the sole disinfectant. Hazard control elements for operating granular media filters to reduce microbial risk are outlined in Table 6.4.

Filter performance can be evaluated by various methods, such as on-line measurement of effluent turbidity (from individual and combined filters) and counting of particles or other surrogates for microbes. To provide comprehensive process control for filtration, it may be useful to measure other operational parameters related to filter performance (e.g. rate of head loss).

The riskiest operations to perform with a granular media filter are starting a filter after backwashing, and increasing the filtration rate (Logsdon, Hess & Chipps, 2000). Filters typically perform poorly at first after backwashing, and passage of microbial pathogens during this ripening period can be formidable. Methods to minimize such problems include various start-up strategies (e.g. filtering to waste, allowing the filters to settle after backwashing and starting slowly) and adding a filter aid to the backwash water supply during the final minutes of the backwash process. Passage of particles and microbes at the end of a filter run can be avoided by taking the filters out of service before head loss becomes terminal, or turbidity or particle counts increase. In many systems, backwash of filters is simply based on the filter run time, to avoid any decrease in water quality at the end of a filter cycle.

Table 6.4 Hazard control elements for granular media filtration

Potential control strategies	Control measures
Monitoring of process control	On-line turbidity or particle counting Flow rate Head loss rate
Minimize filter ripening, breakthrough	Filter to waste Slow start of filters Allowing filters to settle after backwash Add coagulant to wash water supply Avoid terminal head loss
Minimize changes in filtration rate	Surface loading rate Effective sludge removal Settled water turbidity or other process indicator
Effective backwash cleaning	Proper bed expansion Media agitation by air or mechanical washers

Changes in the filtration rate are often unavoidable; for example, when one filter is taken off-line for backwashing. An increase in filtration rate can be detrimental to filtered water quality (Cleasby, Williamson & Baumann, 1963; Fitzpatrick, Campbell & Cable, 1999). The impact can be minimized in various ways; for example, by slowly increasing the filtration rates for the filters remaining in service, or by decreasing plant production while a filter is temporarily out of service.

Also critical to the functioning of granular media filters is the cleaning of the filters during backwash. If not performed correctly, cleaning can lead to clumping of the filter media (formation of mud balls), improper distribution of the media (formation of mounds), destratification of the multimedia layers or media washout. To clean the media grains properly, the filter bed must be fluidized as well as scoured (either mechanically or by air).

6.5 DISINFECTION

In most conventional treatment processes, an adequate level of disinfection is critical for reducing microbial risk to acceptable levels (Table 6.5). Microbial pathogens include highly diverse groups and it is impossible to monitor the survival of all pathogens. Estimating the level of inactivation of more resistant microbial pathogens, by applying the CT concept (disinfectant concentration and contact time) for a particular pH and temperature, ensures that more sensitive microbes are also effectively controlled. The CT concept can sometimes be as simple as providing a certain disinfectant residual for a prescribed contact time.

Table 6.5 Hazard control elements for disinfection

Potential control strategies	Control measures
Indirect monitoring	Disinfectant dose and/or residual Contact time pH, temperature
Direct monitoring	Coliform, *Escherichia coli* and/or other treatment indicators Surrogates: bacteriophage, spore-forming bacteria

The use of indirect monitoring methods depends on the type of disinfectant used (Haas, 1999). For example, control of chlorination systems is often based on measurements of residual chlorine; control of systems using ozone can be based on off-gas ozone monitors or measurements of the dissolved ozone residual; and control of UV systems can be based on continuous monitoring of light absorption and control of lamps to deliver a particular energy intensity.

To assess the inactivation efficiency of the disinfection process, indicator organisms are often used. Typical indicators include total coliforms, faecal coliforms and heterotrophic bacteria, as measured by heterotrophic plate count (HPC). Other indicators may include bacteriophage, aerobic spore-forming bacteria or *Clostridium* oocysts.

6.6 DISTRIBUTION SYSTEM

Protection of the distribution system is the last and one of the most important of the multiple barriers necessary for provision of safe drinking-water. Any microbial contamination at this point has a high probability of resulting in public health risk, even if previous control steps have been applied effectively. Because of the extensive nature of the distribution system, with many kilometres of pipe, storage tanks, interconnections with industrial users and the potential for tampering and vandalism, opportunities for microbial risk do occur (Geldreich 1996; Geldreich & LeChevallier, 1999; Ainsworth, 2004). Hazard control strategies should focus on three essential elements:

- maintaining the quality of the treated water by adequate maintenance of the distribution system;
- minimizing bacterial growth;
- preventing recontamination of the water during distribution (Table 6.6).

Fundamental to the quality of the treated water is the proper operation and maintenance of the pipe system. The WHO publication *Safe piped water: Managing microbial water quality in piped distribution systems* (Ainsworth, 2004) provides comprehensive guidance on the management of distribution system operation and maintenance. It includes guidance on development of a monitoring program for water quality and other parameters, such as pressure in the distribution system. Control measures include using a more stable secondary disinfecting chemical than is used in primary treatment (e.g. chloramines instead of free chlorine), reducing the time that water spends in the system (e.g. avoiding stagnation in storage tanks and looping dead-end sections), replacing pipes, flushing and relining, and maintaining positive pressure in the distribution system.

Critical factors for controlling the replication of bacteria in finished drinking-water are:

- maintenance of a disinfectant residual
- limitation of biodegradable organic material
- control of corrosion.

Other parameters, such as temperature, construction materials and detention time are also important, but may not be easily controlled. In the absence of a disinfectant residual, the permissible level of biodegradable organic carbon may be very low.

Preventing recontamination of the treated water is the primary focus of a cross-connection control program. Devices to control backflow and back-siphonage should be installed at any location that may pose a risk to the treated water (e.g. industrial users, mortuaries, hospitals, tanker trucks and street cleaners). Hydraulic surges caused by rapid changes in pump or valve operations may cause transient negative pressures that are not recorded by conventional pressure monitors (LeChevallier, 1999). Detecting and controlling leaks can limit the opportunities for entry of microbes during negative pressure events.

Table 6.6 Hazard control elements for distribution system protection

Potential control strategies	Control measures
Distribution system maintenance	Flush and clean tanks regularly Minimize stagnation Maintain and replace infrastructure Monitor to detect areas of water quality degradation
Control of bacterial growth	Maintain an effective disinfectant residual Reduce biodegradable organic carbon Control corrosion
Cross-connection control and avoidance of transient pressure	Institute a cross-connection control programme Maintain positive distribution water pressure Avoid hydraulic surges that may create transient negative pressures Control leakage