3

CAPABILITIES OF WATER SAFETY BARRIERS

3.1 INTRODUCTION TO WATER QUALITY

Over the past 50 years, water quality has emerged as a major subject of scientific inquiry. A simple measure of the development of scientific fields is the record of dates when research-focused, peer-reviewed journals for such fields emerge. The first journal of the predecessors of the Chartered Institution of Water and Environmental Management has been published since 1895, the *Journal of the American Water Works Association (JAWWA)* has been published since 1914 and the journal for the Water Environment Federation (now *Water Environment Research*) has been published under several names since 1928. Yet, the first major international peer-reviewed journal specifically devoted to research on water quality, *Water Research*, only began publishing in 1967.

Today, there are an enormous number of scientific and professional journals emphasizing various aspects of water quality, making it increasingly difficult even for specialists to remain current in this field. For a newcomer, or for those whose field is management or public health, this growing body of water quality literature is intimidating. Yet, it is not necessary to absorb all of the overwhelming detail

available to appreciate what measures are most important to achieve effective water treatment performance and to assure safe drinking water. Arguably, some of the outbreaks in recent years may have been caused by a failure to distinguish and deal effectively with the most dangerous water quality hazards identified among the rapidly expanding information on various trace water quality parameters.

This chapter provides an overview of water quality and the safety barriers that are commonly relied upon to achieve safe drinking water. Our intent is to make these basic concepts accessible to those from management, health professions or the public who must, on occasion, interact with water treatment professionals.

Measures of water quality have historically been considered under three main categories — biological, chemical and physical — to reflect the primary characteristics of each measure. These divisions also reflect the history of different disciplinary involvement of biologists (primarily microbiologists, with respect to drinking water), chemists and engineers. Increasingly, the boundaries of these disciplines overlap, as do the emerging means that are used to measure water quality parameters. However, the examples provided in Table 3.1 are still a useful starting point for classifying measures of water quality.

Table 3.1 Major water quality parameter classes

	Physical	Chemical	Biological
Major Characteristics	• can be measured by strictly physical means	• detection may require chemical reaction / process	• organism that may be alive (viable) or dead
	• treat by physical or chemical means	• treat by physical, chemical or biological means	• treat by physical, chemical or biological means
Parameters relevant to infectious disease outbreaks	• turbidity • temperature • colour	• pH • alkalinity • chlorine demand	• viruses • bacteria • protozoa

Water quality parameters can also be classified according to the physical characteristics relevant to treatment options. Water treatment processes have an inherently limited range of capabilities. They can react with the substance to be treated in a chemical, physical/chemical or biochemical reaction that alters the chemical structure of the substance in some beneficial way or they can attempt to separate the substance from the water by physical means such as sedimentation, filtration or volatilization. Volatilization has little direct relevance to the pathogens involved in waterborne disease outbreaks; however, it is indirectly involved because some disinfectants (e.g., chlorine, ozone) are added as gases and must dissolve to achieve disinfection. Parameters

contributing to drinking water odour, including chlorine gas and its disinfection by-products, are also affected by volatilization (Froese et al., 1999).

Solubility is a useful characteristic for categorizing the relationship between a water quality parameter and the water medium. Materials that are truly interspersed at a molecular or molecular complex level amidst surrounding molecules of water are considered *dissolved*. Water is closer to being a universal solvent than any other liquid on earth. Although many substances are virtually insoluble in water, most of these will have some sparingly small level of solubility, making it essentially impossible to attain absolutely pure water. Even as rain falls through unpolluted air, it dissolves trace gases (mainly carbon dioxide) and scavenges fine particles (e.g., pollen, dust) on its pathway to earth. Consequently, even the most pristine water sources have water that contains a range of trace chemicals. These generally pose no health risk to humans; in fact, removing essentially all dissolved minerals from water by various treatment processes can make the resulting water unhealthy if used as the major source of fluid consumption.

Colloidal particles are aggregations of matter that are larger than individual molecules or complexes of molecules. They can be distinguished from the water medium, but are too small to settle or separate at any useful rate because their size keeps them dispersed among the moving water molecules. *Suspended particles* are aggregations large enough to settle and separate from water over time. The classes of particles (non-dissolved), expressed in terms of the time to settle a 1 m distance, are presented in Table 3.2.

Table 3.2   Natural settling times for small particles (adapted from *Principles and Practices of Water Supply Operations: Water Treatment*, 3rd Edition, by permission. Copyright ©2003, American Water Works Association)

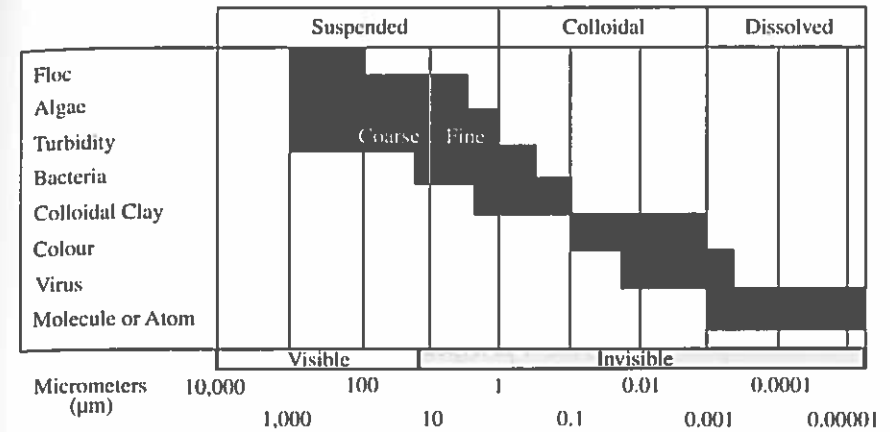| Nominal Particle Diameter, µm	Representative Particle	Time required to settle 1 m
		Will settle – in practice
10,000	gravel	1 second
1,000	course sand	10 seconds
100	fine sand	2 minutes
10	silt	100 minutes
		Will not settle – in practice
1	bacteria	180 hours
0.1	colour colloids	760 days
0.01	fine colloid	21 years
0.001	molecules	>210 years

Figure 3.1 Size range of substances in water (adapted from *Principles and Practices of Water Supply Operations: Water Treatment*, 3rd Edition, by permission. Copyright ©2003, American Water Works Association)

These particle distinctions are made on the basis of operational definitions rather than theoretical considerations. In terms of treatment technologies, dissolved substances will pass a membrane microfiltration process, but most will not pass reverse osmosis. Colloidal particles are not removed effectively by sedimentation or by the direct straining of granular media filtration. These fine particles must be destabilized to allow them to adsorb to filter media or to form larger aggregates that can be removed by the physical straining effect of filtration processes.

The size distribution (effective particle diameter assuming spherical shape) of various particles is summarized in Figure 3.1. This figure spans a billion-fold (10^9) range from smallest to largest. This reality should signal that no single treatment process can deal with the full range of water quality parameters; that is, there is no universal treatment method. The treatment processes discussed below have moderately broad removal capabilities within their functional range.

The nature of substances in water in relation to the particle categories is represented in Figure 3.2. This classification scheme can be expanded in detail for other purposes, but this form is presented to orient the waterborne pathogens and parasites among the other water quality parameters.

Infectious agents are organic, either suspended or colloidal (only the latter are considered in this book), and must be viable (able to reproduce) to be capable of causing infection and disease.

Figure 3.2 Classification of water quality parameters (adapted from Hrudey, 2002b)

3.2 SOURCE WATER PROTECTION

Although completely pure water is not attainable, extremely high quality water can be found in nature in either pristine surface waters or high quality groundwater sources. Far-sighted human settlements have valued such water sources because protecting this quality pays major dividends for health and quality of life of the communities they supply. Some major cities such as New York, Seattle and Melbourne have been fortunate to have long ago established protected drinking water supply catchments, which are now the envy of other communities because of the consistently high water quality that they provide. Although we now realize that wildlife poses a microbial contamination risk to otherwise pristine, protected watersheds (e.g., Victoria, B.C. case study, Section 4.5.17), these risks are manageable provided they are recognized.

Once human developments occur in a watershed (catchment) for either surface or groundwater, the range and magnitude of water quality problems grow substantially along with the difficulty in successfully managing them. Development, once allowed, cannot be easily reversed. Treatment requirements imposed on point sources of pollution will inevitably remove only some fraction of pollutants and the greatest contributions of pollution will often come from diffuse, non-point sources of pollution that are the most difficult to manage. Likewise, water is a multiple-use resource demanded by agriculture, process industries, tourism and ecological habitats, making the management of competing water interests a major challenge that will only grow in difficulty with continuing population and economic growth. Yet, drinking water usually places the highest quality demand on water resources. Society needs to assure that competing water use demands are satisfied in a manner that will not allow other valid water users to externalize their true costs by polluting water needed for critical uses, such as drinking water supplies. These multiple factors combine to make source water protection one of the most complex resource management challenges facing modern societies. Clearly, the full range of these issues is beyond the scope of this book.

Some key features of source water characterization and protection in relation to drinking water safety have been effectively captured by Medema, et al. (2003), providing an excellent summary of the key characteristics of pathogens in source waters. Particularly relevant to the discussions that follow in this chapter is a summary (Table 3.3) of the typical concentrations of pathogens and indicator organisms found in domestic sewage, which remains the most common source of pathogen contamination and resulting drinking water outbreaks.
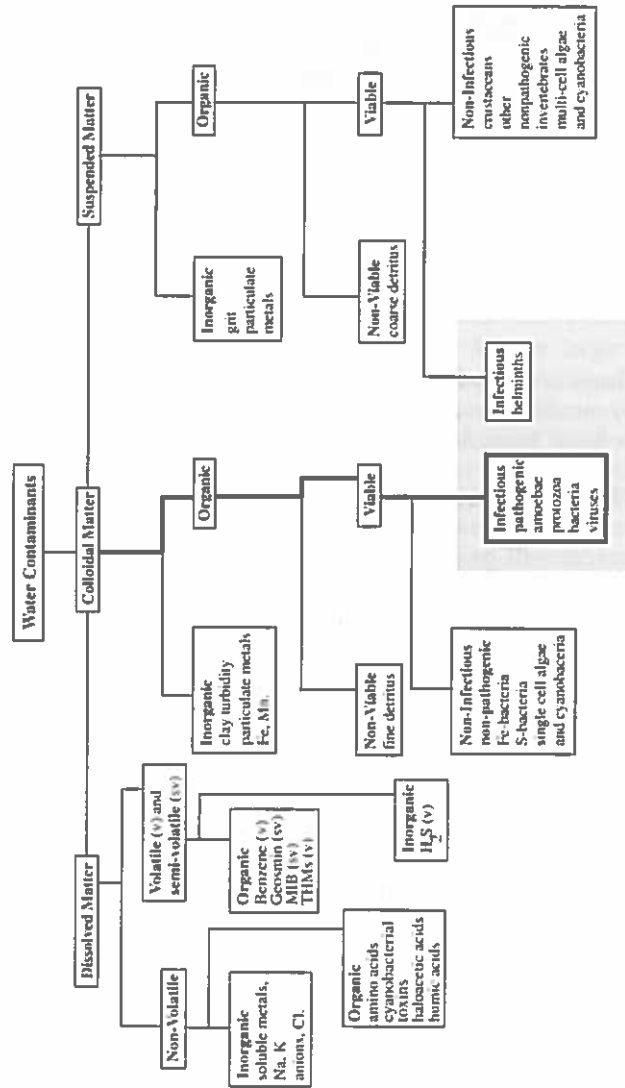
Table 3.3 Typical concentrations of enteric pathogens and bacterial indicators in raw and treated domestic sewage (extracted from Medema et al., 2003)

Microorganism	Raw sewage	Secondary treated effluent
	numbers / L	numbers / L
Pathogens		
Parasites		
Cryptosporidium spp.	1,000 – 10,000	10 – 1,000
Giardia spp.	5,000 – 50,000	50 – 500
Viruses		
Enteroviruses	10 – 100	1 – 10
Norwalk-like viruses	10 – 1,000	1 – 100
Rotaviruses	10 – 100	1 – 10
Bacteria		
Salmonella spp.	100 – 10,000	10 – 10,000
Indicator organisms		
Coliforms	$10^7 – 10^9$	$10^6 – 10^8$
Thermotolerant coliforms / *E. coli*	$10^6 – 10^8$	$10^5 – 10^7$

The large numbers of organisms typically found in sanitary sewage can place considerable stress on the removal capability of water treatment processes. This will be particularly challenging when contamination sources are intermittent with occasional severe peaks. Furthermore, pathogens are typically not uniformly distributed in water, as implied by average concentration numbers, making the maintenance of consistently high treatment performance necessary to avoid passage of occasional fine particle clumps containing enough pathogens to infect any consumer unfortunate enough to draw a glass of such contaminated drinking water.

3.3 CONVENTIONAL WATER TREATMENT PROCESSES

The practice of conventional drinking water treatment has been widely established for over 100 years. These technologies were originally modeled on the processes of subsurface filtration that naturally purify high-quality groundwater sources. As the water demands of our burgeoning urban areas have driven the need for escalating volumes of safe water, engineering has adapted these basic processes to make them more suitable to servicing large urban areas. However, the basic concepts were largely established early in the 20th century and experienced only minor refinements prior to the 1970s. These conventional treatment processes have typically been combined as shown in Figure 3.3 for surface water sources.

Conventional treatment processes function best under consistent conditions; they experience increasing difficulty in performing under conditions of rapid water quality change. Treatment reliability can be improved by providing raw water

storage wherever possible. Otherwise, effective monitoring strategies must be developed for critical parameters that influence treatment performance.
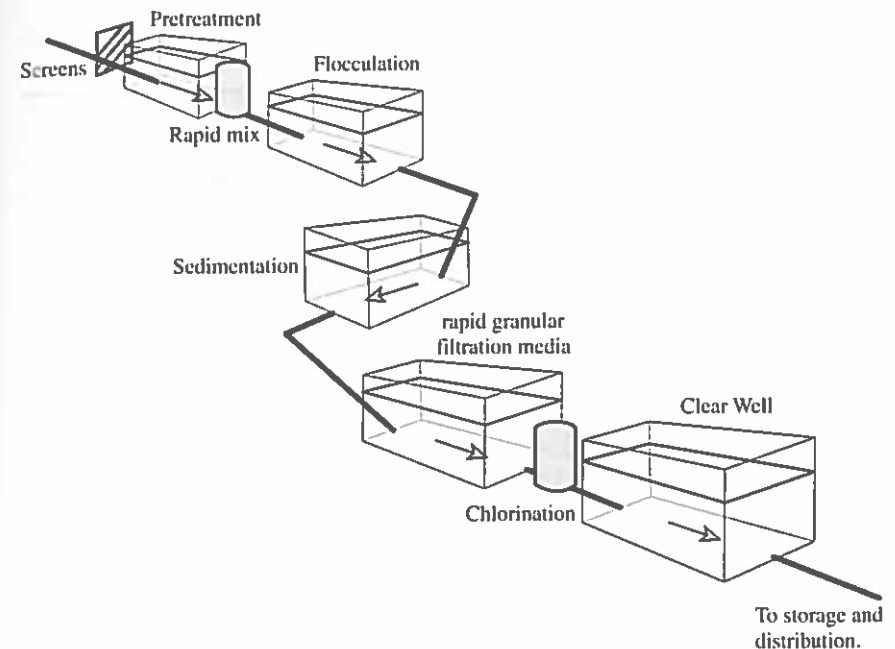

Figure 3.3 Conventional water treatment processes for surface water supplies

3.3.1 Coagulation, Flocculation and Sedimentation (Clarification)

Colloids remain in suspension because they are too small to settle at a significant rate. As well, an individual colloid typically has a charged surface that repels its neighbours; this repulsion effectively keeps the small colloids from coalescing into larger aggregates that could settle out, given their increased settling velocity. Coagulation deals with destabilizing the charge repulsion and flocculation deals with the coalescence of the destabilized particles into large aggregates or flocs.
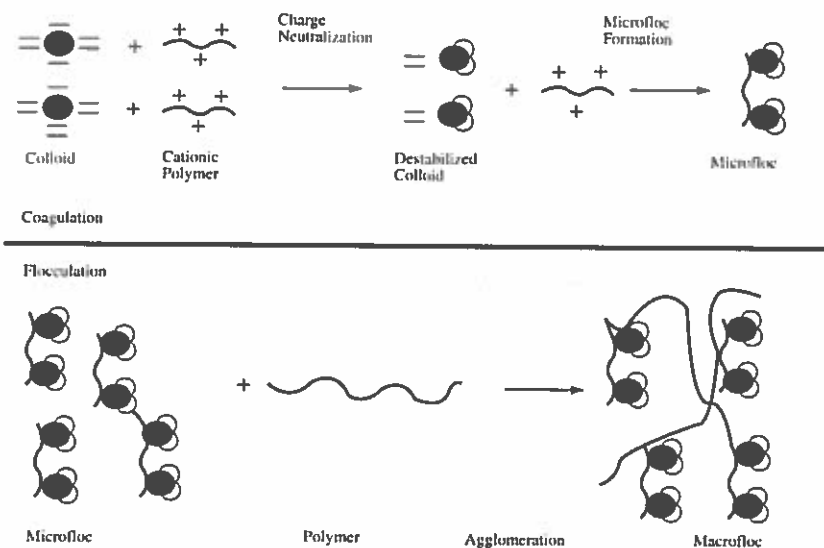
Coagulation

Flocculation

Figure 3.4 Microfloc and floc formation (adapted from *Principles and Practices of Water Supply Operations: Water Treatment*, 3rd Edition, by permission. Copyright ©2003, American Water Works Association)

Coagulation begins by first destabilizing the surface charge to create microflocs (Figure 3.4). This step requires the addition of a charge-neutralizing (cationic) coagulant polymer (either organic or inorganic) to destabilize the negative surface charge on most colloidal dispersions. For this to be effective in a flow-through process, the coagulant chemical, which typically converts into active form in a matter of seconds when added to water, must be added in the correct amount and must be dispersed quickly and evenly by rapid mixing. Alum (aluminum sulphate), the most widely used drinking water coagulant, reacts quickly with alkalinity (capacity of the solution to accept H$^+$) to produce positively charged (cationic) polymers of aluminum hydroxide. These polymers become microflocs that destabilize and attach to the negatively charged colloids. The pH (negative logarithm of the H$^+$ concentration) in the range of 5.8 to 8.5 and sufficient alkalinity must be available for alum; otherwise, it will not react as described and no effective coagulation will be achieved.

Other coagulants often used in water treatment include ferric chloride, polyaluminum chloride and sodium aluminate. Coagulant aids are added to enhance the treatment process by improving coagulation, promoting more resilient, denser or larger floc, reducing temperature sensitivity, reducing the primary coagulant dose and reducing the quantities of sludge requiring disposal. Coagulant aids include activated silica, weighting agents (bentonite clay,

powdered limestone or powdered silica) and cationic polyelectrolytes (organic polymers). Polyelectrolytes can be used alone as coagulants, but they will achieve more effective and consistent turbidity removal when used with a primary coagulant.

Once the charge has been destabilized, conditions for agglomeration of the destabilized colloids must be promoted. Agglomeration is the process of flocculation, which is promoted by gentle mixing and is often achieved by adding an organic polymer flocculant to assist the process. These aids are typically anionic or nonionic polyelectrolytes to maintain and enhance agglomeration. If they are used alone, they will not achieve effective coagulation.

If alkalinity-demanding coagulants like alum are used and the natural alkalinity of the raw water is insufficient, it may be necessary to increase alkalinity to achieve effective coagulation. Chemicals suitable for raising alkalinity include lime, soda ash, caustic soda and sodium bicarbonate. Accurate dosing of these water treatment chemicals requires effective chemical handling facilities to ensure that quantities are accurately controlled. These facilities require regular maintenance because the chemicals may be corrosive or sticky, making it challenging to keep process equipment operating effectively. As noted earlier, it is critical to have rapid-mix facilities to disperse these chemicals effectively in the water to be treated.

After coagulation, floc formation requires appropriate residence time and gentle mixing conditions. If flocculation is not achieved, a condition described as pinpoint floc can arise leaving flocs too small for effective removal by sedimentation before filtration. Flocculation is promoted by using paddle mixers and directing water flow through baffled basins. These measures promote gentle turbulence while minimizing short-circuiting and ensuring adequate residence time.

Process problems that commonly arise in coagulation and flocculation include low water temperature, weak floc and slow floc formation (AWWA, 2003). Cold water temperatures interfere with coagulation and flocculation by increasing the settling rate of the floc, leading to excess floc carry-over from sedimentation to the filtration process. Weak floc leads to overloading of the filters, as well as reduced filter turbidity removal. This problem often occurs if the rapid mixing stage of chemical addition was ineffective or if the gentle mixing in the flocculation basins is inadequate. Slow floc formation often occurs with low-turbidity waters and indicates insufficient particulate matter to combine with the coagulant to yield an effective, settleable floc blanket. Responses may include recycling the settled floc to build up more material for the added coagulant to combine with (similar in concept to the solids contact unit described below) or adding a weighting agent such as bentonite to increase the turbidity available for capture. If slow floc formation is caused by

insufficient alkalinity, the alkalinity will need to be increased by adding lime or soda ash.

Sedimentation, or clarification, normally follows. This separates the flocs that have been formed to entrap the colloidal and suspended materials in the raw water. Sedimentation, using a rectangular or circular clarifier, exploits gravity settling, which is governed primarily by particle diameter. Lesser factors are particle density and water temperature, which govern water viscosity. A clarifier must maintain quiescent conditions that will allow the small flocs to settle. Turbulence or short-circuiting can allow the flocs to remain in suspension and be carried over to the filtration process, where they will create problems with shortened filter runs and poor turbidity removal. The settled floc is collected at the base of the clarifier as sludge, which is often thickened (de-watered) for disposal in a landfill. Filling the clarifier tank with tubes or plates can increase the settling capacity per unit volume of clarifier (Figure 3.5). These tubes shorten the vertical distance that any individual floc needs to travel before it reaches a surface for sludge collection.
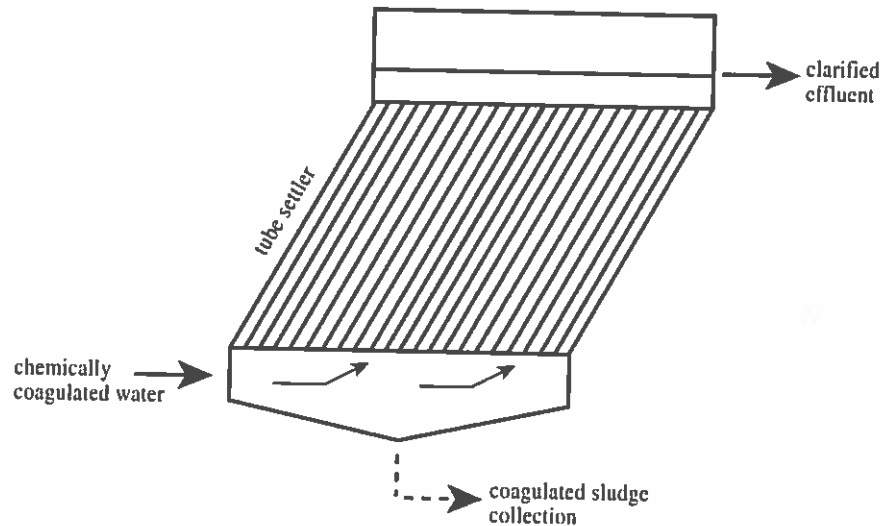

Figure 3.5 Tube settlers to increase clarification capacity

A solids contact unit (SCU) is another variation of a clarifier. The SCU combines the flocculation and settling into a single upflow clarifier unit, directing the coagulated flow to travel upwards through an existing sludge (floc) blanket. The floc should agglomerate when it contacts the solids in the sludge blanket. Although SCUs offer substantial advantages in effectiveness and

reduced size, they can be more easily upset by a sudden change in water temperature or flow rate than a conventional clarifier. Their operation requires close monitoring of solids concentration and settling rates with measurements required at least twice daily and more frequently when water conditions are changing.

Flotation is an alternative method of clarification achieved by producing finely dispersed air bubbles that attach to the flocs and cause them to float, allowing them to be skimmed off the clarifier surface. This process has been more widely used in industrial water treatment than in municipal drinking water treatment, but flotation has been found to be effective for treating water containing algae.
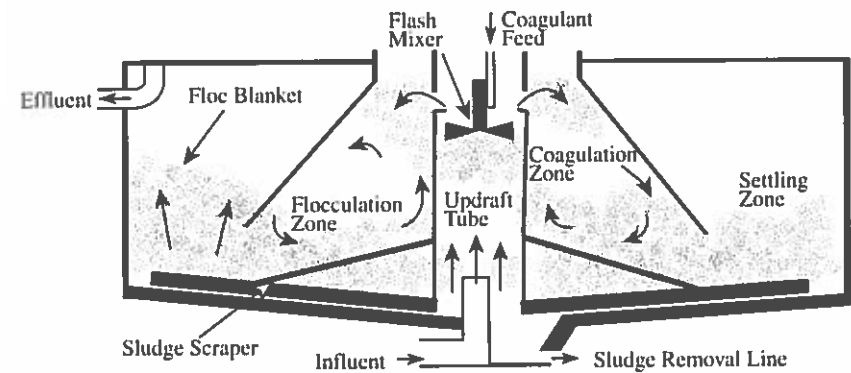

Figure 3.6 Solids contact unit (SCU) up-flow clarifier

The clarification process must be effective to ensure optimum filtration. Some treatment plant designs use direct filtration, whereby the coagulated and flocculated water is not clarified, but is fed directly to the filters. This shortcut obviously leads to higher filter solids loading rates and may contribute to inadequate turbidity removal. The direct filtration option may be appropriate for raw water of consistently low turbidity and colour. The performance of clarification is monitored by measuring the turbidity of the clarified effluent, preferably on a continuous basis for each filter to track performance changes.

Beyond poorly formed floc, operating problems with clarification include short-circuiting, wind-induced turbulence, density currents and algae or slime growth. Short-circuiting involves water traveling through the clarifier much faster than the nominal average detention time (estimated as the clarifier volume divided by the average flow rate). If short-circuiting occurs, it can reduce detention time so much that particle removal by sedimentation is inadequate.

Wind can also contribute to short-circuiting in open settling basins. Problems with short-circuiting, usually a result of poor clarifier design, can be revealed by tracer studies.

Density currents arise when water with a higher solids content or lower temperature is added, making it denser than the surrounding water in the clarifier. In this case, the denser flow sinks to the bottom of the clarifier, where it may disrupt the sludge blanket and displace currents of sludge upward, leading to carry-over of solids into the clarifier effluent. This condition is usually a result of a clarifier design unsuited to local operating conditions.

Algae or slime often grow in open basins exposed to sunlight. This growth may cause taste or odour problems, as well as contributing to solids loading on the filters when cells grow or biofilms detach.

3.3.2 Filtration

The level of suspended and colloidal matter removal that can be reliably achieved by clarification is not adequate to assure drinking water of sufficiently low turbidity. Until the past decade, turbidity guidelines were specified primarily for aesthetic quality (i.e., water clarity) and a target of less than 5 NTU was sufficient for this purpose (WHO, 1993). The desirability of the lowest turbidity possible — less than 1 NTU for disinfection purposes — was noted. This concern arises because substantial turbidity may allow individual pathogens to be shielded from the disinfectant within turbidity particles and because the chemical reaction of disinfectant with turbidity particles consumes disinfectant and thereby increases the disinfectant demand.

Turbidity levels of 5 NTU could be achieved routinely by coagulation–flocculation–clarification–filtration. With the emergence of *Giardia,* and more recently *Cryptosporidium,* as serious problems for drinking water safety, turbidity targets have dropped from 0.5 to 0.3 NTU and are now commonly below 0.1 NTU. Consistently achieving these levels with conventional water filtration processes is possible, but the performance of the filters must be optimized. Excessive turbidity can also be correlated with taste and odour problems or with promoting biofilm (slime) growth in the water distribution system.

Filtration can be achieved by directing water flow through either granular media or through porous membranes. Although membrane processes are rapidly growing in applications worldwide, granular media filtration has been used most commonly for conventional water treatment plants. Flow through this media can be driven by either gravity or applied pressure, but gravity filters are more common. Various granular media can be used in this process; the dual media combination of sand (of carefully controlled particle size) and anthracite is the most common. Granular activated carbon has typically been used where some adsorption of soluble organic contaminants is required. This discussion will

focus on gravity-driven granular media filtration because this is the process most widely used for municipal drinking water.

Gravity filtration processes are most commonly applied in one of three process types: slow sand filters, rapid sand filters or high-rate, multi-media filters. The differences in design and operating characteristics are listed in Table 3.4.

Table 3.4 Comparison of gravity filter characteristics (adapted from *Principles and Practices of Water Supply Operations: Water Treatment*, 3rd Edition, by permission. Copyright ©2003, American Water Works Association)

Characteristic	Slow sand filters	Conventional rapid sand filters	High-rate multi-media filters
Filtration rate (m/h)	0.1	5	7.5 – 20
Media	sand	sand	sand, anthracite and possibly garnet
Vertical distribution of media	unstratified	stratified: fine to coarse	stratified: coarse to fine
Filter run Duration	20 – 60 days	12 – 36 hours	12 – 36 hours
Flow resistance as head loss (m)	0.06 initially to 1.2 finally	0.3 initially to 2.4 or 2.7 finally	0.3 initially to 2.4 or 2.7 finally
Proportion of backwash water used	none	2 – 4% of water filtered	6% of water filtered

All granular media filtration processes remove particles by a combination of straining and adsorption (Figure 3.7). Adsorption is particularly important for colloid-sized particles, which include all of the pathogens discussed in this book, because straining alone is not adequate to remove colloidal particles, nor some of the flocculated aggregations of pathogens. Thus, the process of adsorption, aided by a continuing process of agglomeration that will occur in the small channels of a granular media filter, is vitally important to achieving a high level of turbidity removal. These realities reinforce the critical importance of achieving effective chemical treatment before rapid granular media filtration processes.
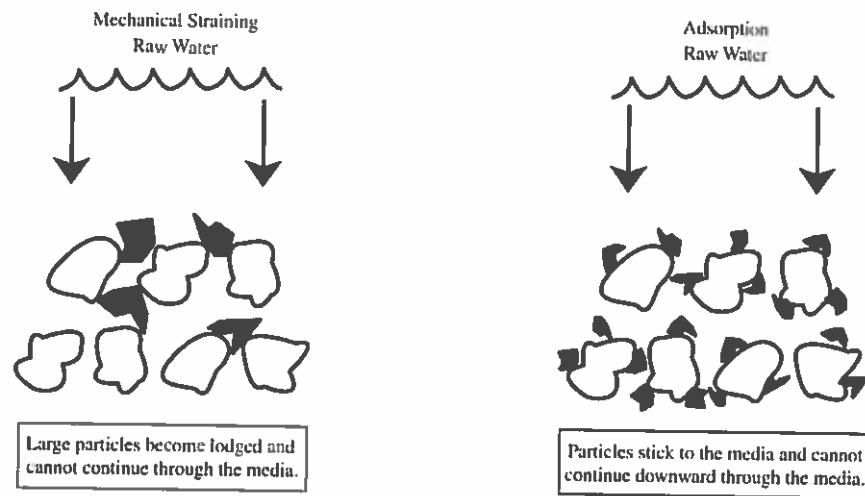
Figure 3.7 Particle removal processes in a granular media filter (adapted from *Principles and Practices of Water Supply Operations: Water Treatment*, 3rd Edition, by permission. Copyright ©2003, American Water Works Association)

Slow sand filtration was the first large-scale engineered water treatment process. The process attempts to replicate the natural process of groundwater purification. This slow infiltration process allows more travel time for coagulation and adsorption, as well as encouraging effective biological activity in a surface layer (*schmutzdecke*) of retained material that accumulates at the top of the filter. Although the slow sand filtration process offers a number of advantages for smaller communities, it encounters freezing problems in very cold climates and requires large areas of land compared with higher rate processes, making it impractical for most large cities.

The filter for rapid and high-rate filtration processes must be backwashed periodically to restore reasonable filtration rates and turbidity removal. This relationship is depicted in Figure 3.8, which shows the characteristics of a typical filter run and a schematic of a filter showing the backwash process. Backwash is critical because effective floc formation produces material that will stick to the granular media and thereby be removed effectively. However, the sticky floc builds up over the duration of a filter run, creating an unacceptable head loss through the filter bed and, ultimately, inadequate turbidity removal. The bed must be expanded to clear it of this retained floc and the media must be cleaned. The backwash flow uses air injection to agitate and scour the granular media particles sufficiently to dislodge adsorbed flocs. Dislodged material will contain high concentrations of pathogens whenever the inlet raw water contains a pathogen challenge. Consequently, the backwash water will also carry this high pathogen load.
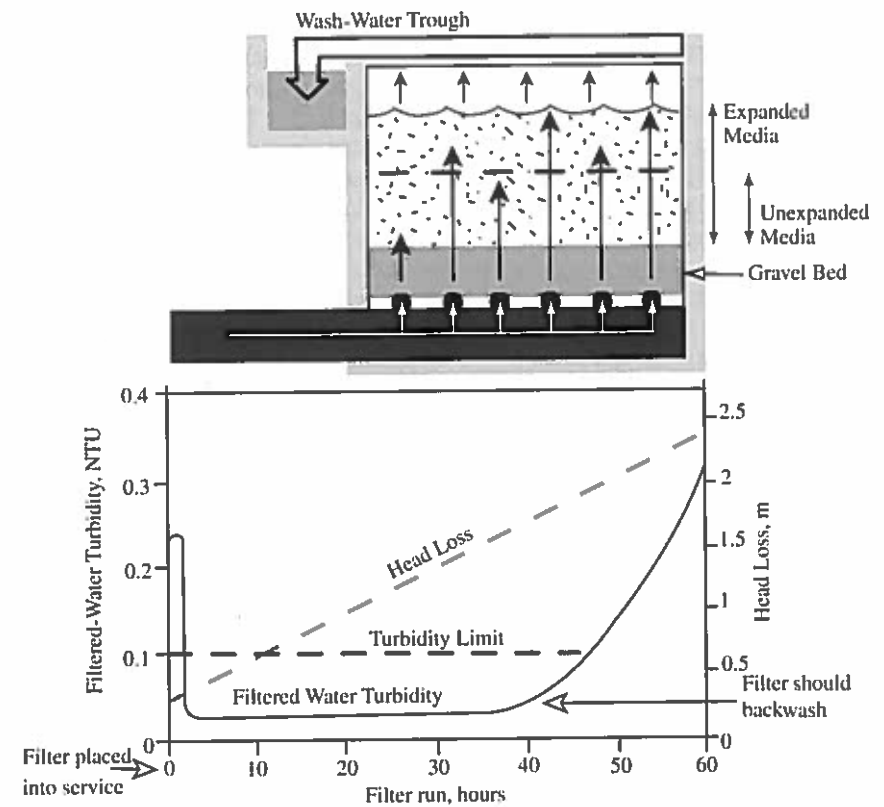
Figure 3.8 Filter run performance and backwash (adapted from *Principles and Practices of Water Supply Operations: Water Treatment*, 3rd Edition, by permission. Copyright ©2003, American Water Works Association)

After the backwash cycle, when filtration is resumed and until the filter ripens, the turbidity will typically be higher and can be expected to have high microbial counts. Running this poor-quality filtered water to waste rather than accepting it as filtered water assures the overall safety of the treated water supply. For this reason, each filter should have continuous effluent turbidity monitoring so that the duration of running filtered water to waste can be optimized.

Recent investigations have shown that the end of a filter cycle (just before initiation of the next backwash) can also be very vulnerable. Even if the effluent turbidity shows only a slight increase, severe impairment of a filter's ability to remove pathogens such as *Cryptosporidium* oocysts can occur (Huck et al., 2002).

Operators must not extend filter runs until complete turbidity breakthrough despite the economic incentive to maximize the length of filter runs.

Filter operating problems can be diverse, but three are particularly common: ineffective coagulation / flocculation, flow-rate control and filter backwashing. The problems with ineffective chemical treatment before filtration are discussed earlier in this chapter. Flow-rate fluctuations can drive trapped contaminants deeper into the filter bed, increasing the chances of breakthrough. When filters are taken out of service for backwashing, the flow rate to the remaining filters will increase. Under these circumstances or those of needing to increase overall flow rates, the change must be gradual to minimize the impact on filter performance. These conditions highlight the reality that conventional water treatment processes perform best under relatively consistent (steady state) conditions. Treatment performance can be seriously degraded when fluctuations in water quality characteristics or flow rates are able to challenge the process. Ineffective backwashing is a major source of problems in conventional filtration. Several problems can be created, including mudball formation, filter bed shrinkage and gravel displacement. These problems accumulate over time and ultimately impair the reliability of the filter bed to provide an effective barrier to turbidity breakthrough.

Floc retained within the granular media will generate an eventual failure mechanism if backwashing does not successfully dislodge the retained floc. If these materials build up over a number of filter cycles, mudballs can be formed by dirty filter media sticking together. After backwashing, these larger masses will settle to the bottom of the filter bed where they become useless to the filtration process. The resulting inactive portion of the filter bed effectively increases flow rates through the rest of the filter and degrades overall filtration performance.

Inadequate cleansing of the filter media can also allow the coated grains to compress unevenly as head loss builds up in a filter run. This uneven compression may open up cracks in the filter bed, allowing short-circuiting downward through the filter bed without adequate filtration and turbidity removal.

Lack of care in controlling flow rates at the start of a backwash cycle can cause the underlying gravel to be displaced upwards into the overlying filter material. This can also be caused by clogging of the filter underdrains leading to differences in backwash flow velocities upward through the filter bed. Ultimately, these displacements may create a sand boil, a phenomenon arising from uneven flow velocities that can create a vertical pathway through the filter bed with little granular media left over the gravel. A sand boil will allow the water being treated to short-circuit or bypass effective filtration through the full depth of the granular bed.

Overall, the operation of water treatment filters requires skill and experience on the part of the operator. This brief overview of water treatment systems

cannot fully address all of the important aspects that must be understood about filter operations. There are readily accessible reference works that can provide considerably more detail on the operation and maintenance of filters (Hiltebrand et al., 2000; Logsdon et al., 2002).

Recognizing some of these major challenges should help readers to appreciate what has failed in a number of waterborne outbreaks. Inadequately trained or inexperienced operators may not be able to achieve optimum or even effective turbidity removal over an extended period. Operating difficult processes such as filtration with untrained or inadequately trained personnel invites failure. The timing of the failure is not predictable, because it will be controlled by various external events, such as the timing of the raw water pathogen challenge peaks. However, when the factors contributing to an overall system failure occur simultaneously, operator skill will be a critical determinant of whether or not the system fails. Assuring maximum operator skill is likely the most important outbreak preventive action that is readily available.

3.3.3 Disinfection: Chlorination

All the water treatment processes described above contribute to lowering the number of microorganisms that appear in treated water because these processes are explicitly designed to remove suspended and colloidal materials (Figure 3.2). Thus, these processes will remove protozoa, bacteria and viruses (in decreasing order of effectiveness) to some extent. The microbial quality of treated water from these treatment processes will inevitably fluctuate, as a function of both variable loading of microbes and variation of other chemical and physical factors (temperature, flow, turbidity, alkalinity, pH, etc.) that disrupt process performance. An additional process of disinfection is justified by the variable — in some cases inadequate — microbial removal, combined with the need to achieve a high degree of assurance that pathogenic microbes do not reach consumers in numbers and in a condition capable of causing disease. This combination and overlap of treatment capabilities is inherent to the multiple barrier concept of risk management explained in Chapter 6.

For the purposes of this book, disinfection will be discussed primarily in terms of chlorination, because it remains the most widely used and generally the most cost-effective means of drinking water disinfection. Chloramination will be considered as part of chlorination because this disinfection option, like free chlorination, may leave a disinfectant residual, offering some level of disinfection capacity as well as a real-time measurable marker of microbial contaminant demand for chlorine. Other disinfectants that will be mentioned briefly are chlorine dioxide, ozone and ultraviolet radiation. However, for the purposes of this book, focusing on the causes of waterborne outbreaks, the case

studies generally involve some form of failure with chlorine disinfection or a failure to provide any disinfection at all.

All of the common chemical disinfectants are strong oxidants (that is, they readily donate electrons to the substance that they react with). This reactivity allows disinfectant chemicals to disrupt the cellular integrity of microbes sufficiently to prevent them from being able to reproduce and infect the host. Unfortunately, it also causes these oxidants to produce unintentional by-products when they react with the natural organic matter that is present to some extent in source waters (IPCS, 2000).

These reaction products are referred to as disinfection by-products (DBPs) and have been the subject of toxicology and epidemiology studies for more than 25 years, mainly in search of evidence of chronic health effects (e.g., various cancers). The first group of disinfection by-products to be recognized were the trihalomethanes (THMs), a set of compounds in which three of the four hydrogens of methane (CH_4) are substituted by either chlorine or bromine or some combination of these halogens. A recent international review concluded that "*The existing epidemiological data are insufficient to allow a conclusion that the observed associations between bladder or any other cancer and chlorinated drinking water or THMs are causal or provide an accurate estimate of the magnitude of risk*" (IPCS, 2000). Over the past decade, disinfection by-products have been studied for a number of shorter-term health effects, primarily adverse reproductive outcomes. Here again, the evidence and corresponding conclusions are uncertain: "*The existing epidemiological data are insufficient to allow the importance of the observed associations of chlorinated drinking water or THMs and adverse pregnancy outcomes to be assessed*" (IPCS, 2000).

Chlorine may be added to water as a gas (Cl_2) or as a solution made from either sodium hypochlorite (NaOCl) or calcium hypochlorite ($Ca[OCl]_2$). Once dissolved in water, chlorine gas forms a combination of hypochlorous acid (HOCl) and hydrochloric acid (HCl). Hypochlorous acid partially dissociates in water to release hydrogen ion (H^+) and hypochlorite ion (OCl^-). All of the disinfectant capability of the chlorine gas resides with either the undissociated HOCl or the OCl^-. If either sodium or calcium hypochlorite is used as the source of chlorine, each will yield OCl^- upon dissociation in water. The distribution between HOCl and OCl^- is determined by the pH of the water. Because pH represents the H^+ concentration, which is the other product of the dissociation, a low pH (high concentration of H^+) will drive the distribution towards HOCl and a high pH will do the opposite. This distinction is important because HOCl is estimated to be about 100-fold more effective as a disinfectant than is OCl^-, making chlorine disinfection more effective at low pH.

The other aspect of chlorine chemistry mentioned above involves chloramines, disinfectants resulting from reactions of chlorine with ammonia

(NH_3). Increasing doses of chlorine relative to ammonia lead to substitutions of chlorine for the hydrogen of ammonia, yielding monochloramine (NH_2Cl), dichloramine ($NHCl_2$) and trichloramine or nitrogen trichloride (NCl_3). Both free chlorine and chloramines can often be present together and the sum of these two is referred to as the total chlorine.

Intentional formation of chloramines will normally be limited to forming the mono- and dichloramines, which have disinfection efficiencies of 1/150 and 1/80 of free chlorine, respectively. These lower efficiencies raise the question of why anyone would intentionally form chloramines, although some level of chloramine formation is inevitable in surface waters because of the presence of ammonia, amino acids and related organic nitrogen compounds. There are two primary reasons that chloramines are used intentionally, in preference to free chlorine. The first is that chloramines are much more stable over time than free chlorine, making it possible to maintain a chloramine residual in a distribution system whereas maintaining a free-chlorine residual is often difficult. The second relates to disinfection by-product formation, particularly THMs. Chloramines have been found to produce substantially lower levels of THMs when reacting with natural organic matter in water than free chlorine.

Given these characteristics of chlorine as a disinfectant in water, several factors will determine the success of chlorination: residual chlorine concentration (chlorine remaining after initial rapid reactions in water), contact time with water that contains microbes, temperature of the water, pH of the water, presence of particles and presence of oxidizable matter which determines chlorine demand (AWWA, 2003).

The most critical factors for achieving effective disinfection are the residual concentration and the contact time. The combination of these factors is expressed as the CT value, in units of mg-min/L. Studies of disinfection have confronted the reality that under the worst sewage contamination scenarios, microbial numbers in water can be extremely high. Concentrations of pathogens may range from 100,000 to 100,000,000 per gram of feces (Feachem et al., 1983). Such large numbers of organisms in waste sources, compared with infectious doses and the much lower (more cautious) target levels set for disinfection, requires pursuing very high overall disinfection efficiencies.

Typically, for surface water treatment, greater than 99% pathogen removal is required, and levels as high as 99.9%, 99.99% or higher may be required in specific circumstances. These high removal rate targets are typically expressed in terms of log (base 10) removal, whereby 1 log removal is a factor of 10 reduction (90% removal). Using this language, the examples listed above would require from 2 log (99%) to 4 log (99.99%) removal.

Experiments to determine the ability of disinfectants to reduce the numbers of viable microorganisms have found that the log removal rate is typically directly proportional to the CT. This approach means the key to achieving an appropriate degree of disinfection is to maintain an adequate value of the CT.

This requirement is applied to the most resistant pathogen reasonably expected, taking into consideration the degree of challenge posed by the raw water supply and the amount of pathogen removal achieved by other processes. This overall integrated approach should prevent waterborne disease, but the factors of temperature, pH, turbidity and chlorine demand all have a bearing on these considerations (AWWA, 2003).

Temperature substantially affects chlorine disinfection, with disinfection efficiency decreasing as water temperature decreases. This effect is somewhat tempered by the chlorine residual being more stable at lower temperatures, but overall lower temperature means lower disinfection efficiency. This effect is more pronounced with combined chlorine (chloramines) than with free chlorine.

Because water pH plays a role in disinfection efficiency, if pH is raised for corrosion control, disinfection efficiency will suffer. This adverse impact must be considered in designing overall treatment requirements. The form of chlorination will also have a bearing on pH. The use of gaseous chlorine lowers pH, while hypochlorite solutions slightly raise the pH. Overall, the operator should seek to maintain stable pH conditions and provide levels of chlorine dosage that are appropriate for the pH conditions achieved.

Turbidity can pose a problem for disinfection if the particles causing turbidity shield pathogens from direct contact with the disinfectant or if the particles themselves react with the chlorine causing a competing demand. Other non-turbidity dissolved substances can pose a chlorine demand, including soluble organic matter, reduced ions (iron, manganese) and ammonia. The initial chlorine demand is exerted rapidly (seconds to minutes), followed by a more gradual demand exerted over an extended period (hours to days). The level of chlorine demand in the water to be disinfected is a critical factor because if the demand consumes too much of the chlorine dose, the residual chlorine may be insufficient to achieve the required level of disinfection. This concept is expressed as:

chlorine residual = chlorine dose − chlorine demand

Because of this relationship, disinfection requirements are expressed in terms of the chlorine residual, not the chlorine dose. The chlorine residual requirement at treatment will reflect the effect of the intial chlorine demand. Chlorine residual provides a vitally important, real-time measure of whether adequate conditions for disinfection are being maintained. Any sudden change in chlorine demand that reduces the chlorine residual normally needed to cope with the potential challenge of pathogens effectively signals, in real-time, exposure to possibly dangerous contamination.

A general practice to address disinfection requirements was developed by the U.S. EPA for surface water sources. An overall level of resistant pathogen removal is specified and credits towards that overall removal requirement are

given according to the effective degree of pathogen removal provided by other treatment processes (U.S. EPA, 1991; 2003). This approach is illustrated in Table 3.5.

Table 3.5 Disinfection requirements and process credits under the U.S. EPA Surface Water Treatment Rule (Source: U.S. EPA 1991; 2003)

Process credits and disinfection required	Viruses	*Giardia* cysts	*Cryptosporidium* oocysts
Total log removal/inactivation required	4.0	3.0	2.0 to 5.5[a]
Conventional sedimentation/filtration credit	2.0	2.5	3.0
Disinfection inactivation required	2.0	0.5	0
Direct filtration credit	1.0	2.0	2.5
Disinfection inactivation required	3.0	1.0	0 to 3.5
Slow sand filtration credit	2.0	2.0	3.0
Disinfection inactivation required	2.0	1.0	0 to 2.5
No filtration	0	0	0
Disinfection inactivation required	4.0	3.0	2.0 to 5.5[a]

[a]   final requirement depends on monitoring to indicate the degree of *Cryptosporidium* challenge in the raw source water.

Various chemical disinfectants are evaluated for the CT required to achieve a given log removal under specific conditions of temperature and pH. This evaluation is illustrated for various pathogens with free chlorine in Table 3.6. Bacteria are readily disinfected by chlorine while *Cryptosporidium* are extremely resistant to disinfection by chlorine. The CT for 99% removal of *E. coli* is 0.032 to 0.05 mg-min/L and for 99.99% removal it is 0.067 to 0.090 mg-min/L (Hoff & Akin, 1986; Kaneko, 1998). In contrast, the CT for 99% free chlorine and monochloramine inactivation of *C. parvum* at pH 7 and 25°C was reported as 7,200 mg-min/L in one study (Korich et al., 1990). These results cannot be generalized to specific individual situations because of the wide range of factors that can influence the results, but the >70,000 fold higher CT for *C. parvum* oocysts compared with *E. coli* does illustrate the difficulty that oocysts pose for chlorine disinfection.

Table 3.6 CT requirements (mg-min/L) for 99.9% (3 log) removal of specified pathogens by free chlorine (Source: U.S. EPA, 1991)

Pathogen	< 1°C	10°C	20°C
Giardia[a]	137 – 552	73 – 292	36 – 146
Viruses[b]	9 – 66	4 – 33	2 – 16

[a]   Ranges: low CT values for pH<6, conc<0.4 mg/L, high values for pH=9, conc=3 mg/L

[b]   Range: low CT values for pH 6-9, high values for pH 10

Chloramines offer substantial advantages in terms of their ability to maintain a stable residual in a distribution system and their lower production of halogenated disinfection by-products. However, the CT values in Table 3.7 for chloramines are usually substantially greater than those for free chlorine. These values mean that considerable contact time must be ensured if chloramines are going to offer effective disinfection for the more resistant pathogens.

Table 3.7 CT requirements (mg-min/L) for 99.9% (3 log) removal of specified pathogen by chloramines (Source: U.S. EPA, 1991)

Pathogen	< 1°C	10°C	20°C
Giardia	3,800	1,850	1,100
Viruses	2,060	1,070	530

Assuring that a drinking water system avoids short-circuiting of flow through the treatment plant, which would allow some portion of the water to be exposed for much shorter contact times, is a key element of implementing the CT criteria for adequate disinfection. Likewise, treated water storage following the last point of disinfectant application, appropriately designed with baffles or other measures to assure an adequate disinfectant contact time, protects the first customer served by the distribution system.

Within the known limits of its capabilities, chlorination is a reliable and relatively simple disinfection procedure. Chlorination can, however, experience some operating problems, which must be considered. Valves on chlorination equipment may occasionally be stiff, if the valves are packed too tightly, making them difficult to open or to shut completely (AWWA, 2003). From a safety perspective, chlorine leaks from gas chlorination facilities are obviously a serious concern because chlorine gas poses a toxic hazard to operating personnel if they are exposed to substantial concentrations. Chlorine may also damage equipment (e.g., causing leaks) because of its strong oxidizing capability and corrosive properties (arising from its acid-forming potential when in contact with moisture).

Some of the hazards posed by chlorine gas can be avoided by the use of hypochlorite solutions, but these pose their own operational problems. Dosing equipment can clog because of calcium carbonate scaling, particularly for waters that have high calcium hardness and carbonate alkalinity. Dosing pumps may also fail because of broken pump diaphragms (AWWA, 2003). Some failures have occurred because incorrect plumbing of chlorination facilities resulted in chlorine solutions being run to waste rather than treating the water.

Chlorination is often associated with offensive taste and odour problems. Consumers near the water treatment plant may experience problems if a very high chlorine dosage at the plant is used to maintain residuals out to the far reaches of the distribution system. Likewise, a constantly varying chlorine dosage will prevent consumer acclimation. Chlorination also produces odorous

by-products that have been described as swampy or swimming pool-like. In this case, the actual odour-causing agents may be chemical by-products from the chlorination rather than chlorine or chloramine compounds themselves (Hrudey et al., 1989; Froese et al., 1999). Aesthetic considerations must be vital to water providers because aesthetics are important to consumers (Hrudey et al., 1995). Concerns about the unpleasant taste or odour associated with drinking water chlorination feature in a number of the outbreak case studies. In some cases, public concerns about health effects possibly associated with disinfection by-products played a role in compromising disinfection and contributing to the outbreak.

Because the purpose of this book is to improve understanding about how drinking water outbreaks have happened and to make that understanding more widely accessible to non-specialists, a full discussion of disinfection alternatives is beyond our scope. However, Table 3.8, derived from an informative guide on the selection of alternative disinfectants, is provided to summarize some of the choices that may be considered (U.S. EPA, 1999a). This table is updated with new information about the capability of UV disinfection for inactivating the protozoan pathogens (Clancy et al., 2000; Craik et al., 2001; U.S. EPA, 2003).

Table 3.8 Summary of disinfectant capabilities and limitations (Sources: U.S. EPA, 1999; 2003)

Condition	Chlorine	Chloramines	Ozone	UV
Meet *Giardia* <2 log	Y	N	Y	Y[a]
Meet *Giardia* >2 log	N	N	Y	Y[a]
Meet *Crypto* <2 log	N	N	Y	Y[a]
Meet *Crypto* >2 log	N	N	Y	Y[a]
Meet virus <2 log	Y	N	Y	Y
Meet virus >2 log	Y	N	Y	N
Secondary disinfectant	Y	Y	N	N
Operator skill	1	2	5	3

[a]   Original table (U.S. EPA, 1999a) has been updated to consider newer findings (U.S. EPA, 2003)
Y = yes, N = no
Operator skill: 1 is low, 5 is high

3.4 ADVANCED WATER TREATMENT PROCESSES

The designation of coagulation, flocculation, granular media filtration and chlorination as conventional treatment in Section 3.2 is a somewhat arbitrary reflection of the most common surface water treatment technologies used in a number of affluent nations (e.g., Britain, the U.S. and Canada). Over the past three decades (the time frame chosen for waterborne outbreak case studies in Chapter 4), considerable attention has been paid to minimizing the formation of

halogenated disinfection by-products and to improving the performance of conventional technologies for the more recently recognized pathogens responsible for waterborne outbreaks (*Giardia*, *Cryptosporidium*, Norovirus, *Campylobacter* spp. and *E. coli* O157:H7). Of these, only *Campylobacter* spp. and *E. coli* O157:H7 are readily handled by conventional treatment. Conventional treatment with effective filtration and sufficient free chlorine CT can handle *Giardia* well and will likely deal with Noroviruses, although the latter have not been studied for pilot plant removal as has *Giardia*.

In the case of *Cryptosporidium*, advanced treatment or disinfection processes should be considered, in addition to maximizing improvements in performance of other relevant barriers. These advanced processes will not be considered in detail here because the inadequate performance of advanced processes has generally not been a factor in the outbreak case studies reviewed in Chapter 4. Increasingly, advanced technologies are considered for implementation after a serious treatment failure. The advanced technologies considered below (membrane filtration, ozonation and ultraviolet radiation) are limited to technologies offering a major capability for the control of pathogens. Accordingly, other advanced processes, such as granular activated carbon adsorption to control taste and odour, pesticides, industrial solvents, organic contaminants and cyanobacterial toxins will not be discussed.

The most important lesson about any water treatment technology is that no single technology can meet the full range of challenges encountered in treating raw waters to make them safe for public consumption.

3.4.1 Membrane Filtration

Membrane filtration consists of a family of processes that drive water under pressure through a membrane with a controlled pore size. Membrane processes, classed according to their pore size from largest to smallest (operating pressures from lowest to highest), include microfiltration, ultrafiltration, nanofiltration and reverse osmosis. These processes remove substances by a direct straining mechanism in the case of microfiltration and ultrafiltration, while nanofiltration and reverse osmosis achieve a straining effect along with more complex removal processes. All of these processes will remove protozoa and bacteria. Virus removal requires ultrafiltration, nanofiltration or reverse osmosis.

A primary appeal of membrane processes over granular media filtration is that they offer a more direct and less operation-dependent barrier to pathogens. As such, less operational skill is required to assure effective pathogen removal with membrane technology. Of course, such advantages bring their own limitations, with costs being higher, particularly for large installations. The economies of scale available with granular media filtration installations are not readily achieved for membrane installations.

The scope of our coverage precludes consideration of more detail about these technologies, but there are some excellent current reference sources available (AwwaRF, 1996; Duranceau, 2001; AWWA, 2003).

3.4.2 Ozonation

Like chlorine, ozone is a very toxic gas that is also a strong oxidizing agent. Its reactive properties make it effective for disinfecting microorganisms. Unlike chlorine, which is manufactured off-site and delivered to water treatment plants, ozone must be generated on-site and applied immediately: it is too reactive to be made off-site and stored. Ozonation has been used for disinfection almost as long as chlorination and has been far more popular in Europe than in North America. Ozone offers some clear advantages over chlorination, most significantly that it can achieve some disinfection of *Cryptosporidium*. The effectiveness of ozone for this purpose is temperature sensitive and drops substantially at low temperatures, making it less attractive for cold climate applications.

Ozonation does not produce the halogenated disinfection by-products created by chlorination, but it creates its own variety of by-products that pose concerns for water quality and health. Ozonation of natural organic matter in water tends to convert that organic matter into substrates more amenable to supporting the growth of natural bacteria in water, meaning that ozonation, by itself, is likely to promote biological growth within a distribution system. Ozone also leaves no residual for water in the distribution system, an issue that is discussed in the section on distribution systems.

Overall, ozonation demands more skill for generation and operation and is more expensive than chlorination. Ozonation has received considerable research attention over the past 25 years, including having a dedicated research journal, *Ozone Science and Engineering*, published on behalf of the International Ozone Association since 1979. Other recent references on ozone application for drinking water treatment include AWWA (2003) and White (1999).

3.4.3 Ultraviolet Radiation Disinfection

Ultraviolet disinfection (UV) has been in use for the disinfection of microorganisms for as long as chlorination and ozonation, but UV has been regarded of limited utility for medium- to large-scale facilities. UV disinfection relies on transmission of UV radiation through the water to reach target pathogens, so there is some concern about interference from turbidity. However, the increasingly stringent turbidity standards being imposed on water treatment

facilities make any turbidity limitation for the adoption of UV less relevant under current practices.

UV does not produce halogenated disinfection by-products. To date, there is no substantial evidence of UV producing any other disinfection by-products of health concern. There may be problems with fouling of the lamp surfaces for waters that are high in natural organic matter.

UV is effective in damaging the DNA of pathogens, and this mechanism has recently been found to render *Cryptosporidium* incapable of reproducing without killing them (Clancy et al., 2000; AWWA, 2003). This feature, in particular, combined with major advances in the technology for delivering UV disinfection to drinking water, has led to considerable interest in the use of UV disinfection as a supplementary process in addition to a primary disinfectant like chlorine. However, UV, like ozonation, does not leave any residual in the treated water. There are recent references available to provide more details on the application of UV for drinking water disinfection (Mackey et al., 2001; AWWA, 2003).

3.4.4 Other Processes

A number of other oxidation processes have been used in various drinking water treatment applications, including chlorine dioxide, potassium permanganate, bromine, iodine (temporary use only), hydrogen peroxide and various combinations of these chemicals with other oxidation processes. These chemicals may be suitable for specific applications, but as they do not feature substantially in the case studies to follow, they are not discussed further.

3.5 WATER DISTRIBUTION AND STORAGE

A striking benefit of modern drinking water systems is that clean, safe water can be delivered to individual homes available on demand. This remarkable convenience allows high levels of sanitation and personal hygiene that have contributed to the substantial reduction in infectious diseases over the past century in developed nations. Assuring that water remains safe after leaving a water treatment facility to the point of delivery to consumers remains a major challenge for drinking water providers. For most water systems, there is a larger investment in the infrastructure and operations of water delivery than in water treatment, yet the vulnerability of water distribution is often overlooked.

Among 619 waterborne disease (chemical and microbial) outbreaks reported in the U.S. for public water systems, from 1971 to 1998, 113 (18%), were caused by distribution system deficiencies. These included (Craun & Calderon, 2001): cross-connections or back siphonage, corrosion or leaching of metals,

broken or leaking water mains, contamination during storage, contamination of mains during construction or repair, contamination of household plumbing or inadequate separation of water mains and sewers.

Among the outbreaks caused by distribution system failures, 75 (66%) involved microbial pathogens. The remaining 38 chemical incidents involved contamination by: copper (47%), chlordane (8%), nitrite (5%), unidentified herbicides (5%), ethylene glycol (5%), oil (5%) and other chemicals (24%).

One death was associated with ethylene glycol contamination, so the health consequences of chemical contamination can be severe. However, this book is focused on infectious disease caused by microbial pathogens. A disturbing observation was that between 1995 and 1998, 45% of all outbreaks in community water systems were attributable to deficiencies in distribution systems (Craun & Calderon, 2001). As urban infrastructure ages and investment in maintenance has been delayed or ignored — a growing problem across the developed world — the risks of distribution system contamination of drinking water are likely to become more acute. Certainly, these dangers are prominent in the outbreaks reviewed in Chapter 4 and they make a compelling case for devoting careful attention to managing the contamination risks arising in the distribution and storage of drinking water.

Fortunately, the importance of maintaining water quality during distribution has received growing attention in research and practice over the past decade. In addition to a growing body of relevant literature on specific problems, there are some excellent guidance manuals available to any drinking water provider. These offer the opportunity to learn from the negative experience of others and implement best practices in this important element of drinking water safety (U.S. EPA, 1989; Kirmeyer et al., 2000; Pierson et al., 2001; AWWA, 2004).

One specific matter of distribution water quality that deserves mention concerns the maintenance of a disinfectant residual throughout the distribution system. This has been a requirement in a number of jurisdictions (North America, U.K.) where chlorination has been most common. Both ozone and UV, which provide no residual for the distribution system, have been at a disadvantage to chlorine in those jurisdictions. Much of Europe (outside the U.K.) views with skepticism the need for a chlorine residual in the distribution system.

Although there has been evidence suggesting that a chlorine residual provides little effective disinfection capacity for microbial contamination that may arise in the distribution system (Payment, 1999), a chlorine residual does provide an easily measurable indicator of oxidant demand. The capability for real-time warning of potentially major contamination in the distribution system is important, but whether this warning is sufficient to prevent small-scale contamination and endemic disease occurrence is less clear. The arguments for

and against requiring a chlorine residual in distribution systems provide an interesting example of a current debate concerning drinking water safety (Hambsch, 1999; Hydes, 1999; LeChevallier, 1999; Shaw & Regli, 1999; Trybey et al., 1999). However, monitoring and maintenance of a chlorine residual in the distribution system could have prevented or at least substantially limited the scope of some recent fatal outbreaks (Walkerton, Gideon, Cabool) reviewed in Chapter 4.

3.6 RISK MANAGEMENT FOR SAFE DRINKING WATER

Providing safe drinking water is essentially an exercise in risk management. The general concepts of risk and risk management are intuitively understood because most important decisions that people make in their lives involve managing risk in some form. However, intuitive familiarity with risk can cause confusion because different indivduals analyzing a problem can use the same word to mean different things and different words to mean the same thing without ever realizing that they understand the key elements of the problem differently (Kaplan, 1997). Consequently, there is value in being explicit about what a common word like *risk* means when applied to drinking water quality and safety.

The newly revised Australian Drinking Water Guidelines (NHMRC, 2003a) proposed an important distinction between risk and hazard that has also been adopted in the new third edition of the WHO Guidelines for Drinking Water Quality (WHO, 2003c):

- A **hazard** is a biological, chemical, physical or radiological agent that has the potential to cause harm.
- A **hazardous event** is an incident or situation that can lead to the presence of a hazard (what can happen and how).
- **Risk** is the likelihood of identified hazards causing harm in exposed populations in a specified time frame, including the magnitude of that harm and the consequences.

Let us illustrate these concepts with a pathogen. *C. parvum* is a hazard for any surface water system because it is always potentially present by plausible means. A challenge to a water system by a waste source containing *C. parvum* such as a sewage spill is a hazardous event. The risk associated with *C. parvum* is the likelihood that the pathogen will pass through the treatment system to reach consumers in an infectious state and in numbers sufficient to cause illness.

The distinction between hazard and risk is important because any drinking water supply faces an open-ended list of hazards (potential for harm). While it is important for a drinking water provider to attempt to identify and understand as many relevant hazards as possible, the process of producing safe drinking water requires that priorities for action be established on the basis of risk (probability and severity of consequences). If all hazards are treated as equally relevant, risk will not be managed because preventive efforts will be excessive for trivial risks and inadequate for substantive risks (Hrudey, 2001).

A pragmatic perspective on these concepts for drinking water risk management by means of a multiple barrier approach is illustrated in Figure 3.9. These concepts provide a perspective for considering the specific failures revealed in the case studies that follow in Chapter 4. The risk management approach to achieving drinking water safety is developed more explicitly in Chapter 6, after the recurring themes of the outbreak case studies have been considered in Chapter 5.
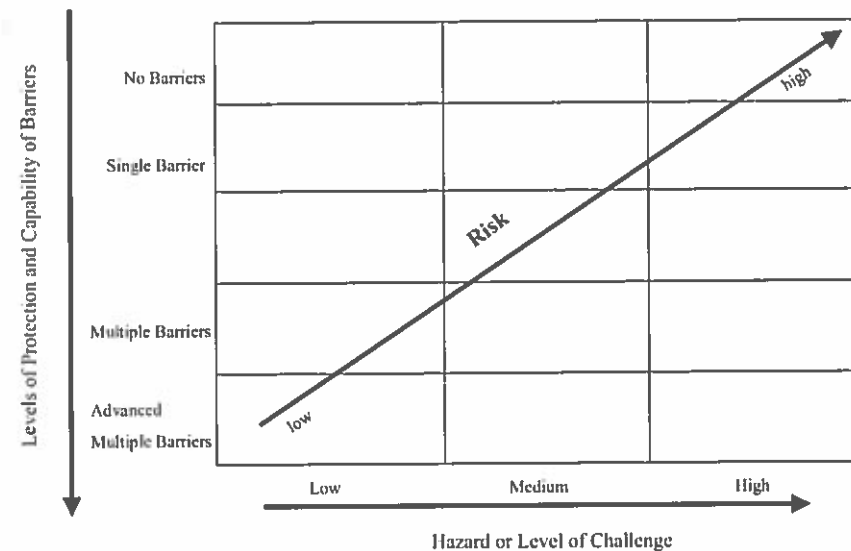

Figure 3.9 Drinking water risk management (Source: Hrudey, 2001)

Effective risk management for any water system requires those responsible to take ownership of the challenges by seeking to know their own system, including the full range of hazards, plausible hazardous events, risks that must be managed with greatest priority and risks that must be planned for even if their likelihood does not warrant immediate action. Risk management cannot be contracted out effectively to others. Advice on developing a risk management

approach may be helpful for getting started, but effective risk management must be based on system-specific local knowledge that is continuously updated as conditions change.

A commitment to protecting public health through a comprehensive and effective risk management approach must be supported at all levels within an organization and needs to be recognized and appreciated by those who are well served by an effective organization if it is to be sustained. In this way, risk management can become an integral element of day-to-day operations rather than being a meaningless expression for public relations.

" 'BE CAREFUL'! ALL YOU CAN TELL ME IS 'BE CAREFUL' ? "

Figure 3.10 Risk management (©2004 Sidney Harris, reproduced with permission)

4

WATERBORNE OUTBREAK CASE STUDIES

4.1 INTRODUCTION

The fatal outbreak in Walkerton, Ontario, Canada in May 2000 has amplified the range of concerns that a water quality manager for a drinking water provider must now consider. Walkerton should affect the drinking water industry for a number of reasons. Justice Dennis O'Connor's Inquiry (O'Connor, 2002a) provides remarkable detail about the multiple failures at many levels in a drinking water supply that was supposed to have been disinfected, monitored and regulated. This tragedy killed otherwise healthy consumers, including a 2-year-old child among the seven who died. This stark reality contrasts with the more common experience of an outbreak that makes many consumers ill for a matter of days, perhaps weeks. In extreme cases, fatalities have generally occurred among the elderly or those already gravely ill.

Citizens in affluent nations do not expect their drinking water to kill them or their neighbours. Given the available means for producing safe water, consumers should be able to expect and should receive safe water. Likewise, our societies normally

Safe Drinking Water

Lessons from Recent Outbreaks in Affluent Nations

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