Drinking Water Chlorination

A Review of U.S. Disinfection
Practices and Issues

American Chemistry Council

Contents

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Foreword

Imagine living in a world without chlorine disinfection of drinking water. It would be a scary place. You would have no idea when a dreaded disease might strike you down or strike down your children or other family members. This is the world that everyone in the U.S. lived in at the turn of the twentieth century. Let's examine one city to highlight both the tragedy and the solution.

Jersey City, New Jersey, was an industrial powerhouse in the early 1900s. With a population that had grown to over 200,000, it had little success finding a water supply that did not end up sickening or killing many of its inhabitants. An effort in the middle of the nineteenth century resulted in the construction of an eight-mile long pipeline to Belleville, New Jersey to tap the lower part of the Passaic River. Untreated water from this source was delivered to the City. The good news was that taking water from the mouth of the Passaic resulted in an abundant supply. The really bad news was that over the next few decades, sewage contamination from Paterson and other New Jersey cities turned the water supply into a cesspool.

The death rate for typhoid fever alone in Jersey City was 85 per

100,000 population in 1896, which was the last year that the Belleville supply was used. There were few U.S. cities with so high a death rate. Use of a temporary water supply improved typhoid death rates down to about 20 per 100,000 for several years. In 1904, a new, untreated water supply was brought in from Boonton Reservoir, but no improvement in death rates was observed. The diarrheal disease death rate for young children in Jersey City in 1900 was horrific—198 per 100,000, or about ten times the typhoid fever death rate.

It was only after the introduction of chlorine disinfection to the Jersey City water supply on September 26, 1908, that the death rate from typhoid fever immediately dropped in half and ultimately was forced to zero. Children stopped dying by the thousands. How did the decision to disinfect the first public water supply in the U.S. come about? We know that hundreds of cities adopted chlorination a few years after Jersey City showed such dramatic improvements in public health. Why did that happen so fast?

As you might expect, there is a book about that. The story of how one man, Dr. John L. Leal, had the courage to add a chemical to a contaminated water supply and change the course of U.S. history is remarkable. He was a physician and a public health expert, and he had seen the devastation that water-borne diseases brought to a community. Dr. Leal was also an expert in the nascent field of bacteriology. His laboratory studies convinced him that small amounts of chlorine would eliminate the pathogens that were sickening and killing adults and children. A court case questioning the "pure and whole-some" character of the Boonton Reservoir water supply gave him the perfect opportunity to try out this

revolutionary concept. The courts agreed with Dr. Leal and gave precedent-setting approval to the use of chlorine to purify water supplies. Dozens of cities paid close attention to the Jersey City court case, and after the court's approval, these cities began installing chlorine feed systems on their own. Before long, all U.S. cities jumped on the chlorine bandwagon and, ultimately, millions of lives have been saved.

We do not have to go back 100 years to see what contaminated water does to a community. The tragedy of not providing safe drinking water to its citizens has been playing out in Haiti over the past six years. A cholera epidemic has been raging in the country since 2010, causing more than 750,000 cases and killing almost 10,000 people with no end in sight. The original source of the epidemic was the Artibonite River that became contaminated possibly from Nepalese peacekeepers there to help deal with the after effects of a massive earthquake. Haitians drank un-disinfected water from that source and the epidemic was born. None of this massive tragedy would have happened if the water Haitians drank from that river was disinfected with chlorine. *Vibrio cholerae*, the bacterium that causes cholera, is particularly sensitive to low levels of chlorine.

The Haitian statistics do not show the daily impact of diarrheal diseases which kill thousands. High levels of chronic dysentery sap the will of a people. It is the deaths of children caused by cholera, typhoid and diarrheal diseases that destroy the fabric of a culture. I spoke with one woman who lost her baby sister to typhoid fever in the U.S. in the late 1940s. The family was devastated and the mother never recovered. Imagine multiplying that tragedy a million-fold and having that tragedy repeat itself year after year.

Of course, many people are still living in that chlorine-free world today and paying the awful price. Tragically, many countries in the developing world have decided against the use of chlorine because of the production of disinfection byproducts. In the developed world, control of disinfection byproducts while using chlorine-based disinfectants has been successful at the same time that cholera, typhoid and diarrheal diseases are kept in check.

If a country is interested in joining the ranks of those in the developed world, they have to provide safe drinking water to their people. Using chlorine in drinking water to kill pathogens will be a key step to obtaining the entry card to that illustrious club.

Reference:
McGuire, M.J. (2013). *The Chlorine Revolution: Water Disinfection and the Fight to Save Lives.* AWWA: Denver, Colorado.

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Executive Summary

The treatment and distribution of drinking water for safe use is one of the greatest achievements of the twentieth century. Before cities began routinely treating water with chlorine, starting in 1908 in Jersey City, New Jersey, cholera, typhoid fever, dysentery, and hepatitis killed thousands annually. As more and more communities began chlorinating and filtering (the physical removal of particulate matter) their drinking water, corresponding death rates declined dramatically.

Providing clean, safe drinking water requires a multi-barrier approach that includes protecting source water from contamination, appropriately filtering, disinfecting, and treating raw water, and ensuring safe distribution of treated water to consumers' taps.

During the conventional treatment process, chlorine is added to drinking water as elemental chlorine (chlorine gas), sodium hypochlorite solution (bleach), or dry calcium hypochlorite. When applied to water, each of these disinfection methods forms free chlorine, which destroys pathogenic (disease-causing) organisms.

Almost all U.S. drinking water treatment plants use some type of chlorine-based process—either alone or in combination with other disinfectants such as ozone or ultraviolet (UV) radiation. Water systems choose disinfection methods based on their own site-specific needs and resources. In addition to controlling disease-causing organisms, chlorination offers additional benefits, including:

- Reducing many disagreeable tastes and odors;
- Eliminating slime bacteria, molds and algae that commonly grow in water supply reservoirs;
- Controlling and reducing microorganism-containing biofilms; and
- Removing chemical compounds that hinder disinfection.

As importantly, only chlorine-based chemicals provide residual disinfectant levels that help control and reduce microbial (re)growth in the distribution system.

The Risks of Waterborne Disease

In 2015, 884 million people worldwide lacked access to a basic drinking water service, while 2.3 billion people lacked even basic sanitation facilities such as toilets or latrines (WHO, 2018a,b). Consequently, these people are more susceptible to disease outbreaks.

Even where drinking water treatment is widely practiced, constant vigilance is required to guard against waterborne disease outbreaks caused by bacteria, viruses, protozoa, and toxin-producing algae. Many important waterborne diseases are zoonotic—caused by pathogens that can spread from animals to humans.

Well-known bacterial pathogens such as toxin-producing *Escherichia coli*, *Salmonella typhi*, and *Vibrio cholerae* as well as viruses, are easily controlled with chlorination, but can cause harmful or even deadly outbreaks given conditions of inadequate or no disinfection. An example occurred in May 2000 in the Canadian town of Walkerton, Ontario. Seven people died and more than 2,300 became ill after *E. coli* and other bacteria contaminated the municipal groundwater supply. A similar and more recent outbreak took place in August 2016 in Havelock North, New Zealand, when 5,000 of the 14,000 residents were sickened after drinking untreated groundwater contaminated with *Campylobacter* bacteria. That outbreak may also have contributed to up to four deaths. Both outbreaks could have been prevented if an adequate residual chlorine disinfectant level had been maintained.

Legionella bacteria in water can cause a serious respiratory infection known as Legionnaires' disease—a form of pneumonia that can be fatal for susceptible populations such as hospitalized patients and the elderly. People can be exposed to *Legionella* when they inhale aerosols or mists from household plumbing, cooling towers, showers, decorative pools and waterfalls, and hot tubs contaminated with *Legionella*. The

U.S. Centers for Disease Control and Prevention (CDC, 2017a) identified *Legionella* as the most common cause of drinking water-associated waterborne disease outbreaks in the United States from 2009 to 2014, and the only outbreaks that resulted in deaths. *Legionella* can be controlled in buildings (premise plumbing) by maintaining an active chlorine or chloramine concentration in the water.

The Challenge of Disinfection Byproducts

Whereas protecting against acute microbial contamination is the top priority, drinking water systems must also control disinfection byproducts (DBPs)—chemical compounds formed unintentionally when oxidants like chlorine and other disinfectants react with naturally-occurring organic matter in source water. In 1974, EPA scientists and a Dutch researcher independently determined that drinking water chlorination could produce a group of DBPs known as trihalomethanes (THMs), including chloroform. EPA set the first regulatory limits for THMs in 1979.

Although the collective research does not definitively show that DBPs in drinking water cause adverse health effects in humans, high levels of these chemicals are undesirable. Cost-effective methods to reduce DBP formation are available and should be adopted where possible. However, the World Health Organization (WHO, 2017; p.173) strongly cautions:

In attempting to control DBP concentrations, it is of paramount importance that the efficiency of disinfection is not compromised and that a suitable residual level of disinfectant is maintained throughout the distribution system.

Between 1991 and 1993, cholera, an acute and deadly diarrheal disease caused by *Vibrio cholerae* bacteria, raged throughout Latin America, claiming almost 9,000 lives and sickening nearly 1 million people. In response to the first appearance of cholera, the Pan American Health Organization promptly issued a directive to promote continuous chlorination of all water distribution and delivery systems. Local officials, however, began encountering pockets of resistance from health officials in Peru and other countries that seemed to stem from concern over DBPs.

In order to meet recent DBP drinking water standards, many treatment plant operators are limiting the amount of natural organic material present within source waters prior to disinfection and/or have chosen to switch to chloramine, produced by mixing chlorine and ammonia, to provide residual disinfection.

Water Security

Drinking water treatment provides one of the most basic elements of life—a reliable supply of safe water. In the post-9/11 reality, protecting and controlling access to these critical infrastructure systems is now a standard part of water system planning and operations.

Disinfection itself is crucial to water system security, providing immediate and lasting protection against biological contamination. Conventional filtration and disinfection processes will remove or reduce the threats posed by numerous potential bioterrorism agents. However, even multiple conventional treatment barriers cannot ensure safety from all biological attacks.

As part of its vulnerability assessment, each water system should consider the transportation, storage, and use of their treatment chemicals, which are simultaneously critical assets (necessary for delivering safe water) and potential vulnerabilities (can pose significant hazards, if released). All security options should be weighed and prioritized considering the unique characteristics and resources of each system, including risk trade-offs associated with each option.

Comparing Disinfectants and the Future of Chlorine Disinfection

Given chlorine's wide array of established benefits, and despite a range of new and ongoing challenges, chlorinated drinking water systems will remain a cornerstone of waterborne disease prevention and public health protection in the United States and abroad. Alternative disinfectants (including oxidants chlorine dioxide, ozone, and UV radiation) are available and, in some cases, appear to be gaining greater use—especially in combination with chlorine and chloramine technologies. Nonetheless, all disinfection methods have unique benefits, limitations, and costs. No single disinfection method is right for all circumstances. Water system managers must consider these factors and design a disinfection approach to match each system's characteristics, needs, resources, and source water quality.

At the global level, safe drinking water continues to be recognized by the WHO and other international organizations as a critical building block of sustainable development. Drinking water chlorination is scalable—it can provide reliable, cost-effective disinfection for remote rural villages, mid-sized communities, and large cities alike, helping to bring safe water to all.

1 Chlorination and Public Health

Of all the advancements made possible through science and technology, the treatment of water for safe use is truly one of the greatest. Abundant, clean water is essential for public health (see **Box 1-1**). Humans cannot survive without water; in fact, our bodies are 67% water! The U.S. National Academy of Engineering (2018) cites water treatment as one of the most significant advancements of the last century (see **Box 1-2** on page 8). Without disinfection and filtration—the physical removal of particulate matter—consumers are at high risk of contracting and spreading waterborne diseases.

Disinfection—a chemical process whose objective is to control disease-causing microorganisms (pathogens) by killing or inactivating them so they cannot reproduce—is unquestionably the most important step in drinking water treatment. By far, the most common conventional method of drinking water disinfection in the U.S. and abroad is chlorination.

Prior to 1908, no U.S. municipal water systems chemically disinfected their drinking water. In some cities, water filtration was already lowering bacteria levels in drinking water, but it was not enough. Individual bacteria and viruses were still passing through filters (WQHC, 2014). Consequently, waterborne diseases exacted a heavy national toll in illness and death.

The Chlorine Revolution: Water Disinfection and the Fight to Save Lives by Michael J. McGuire (2013) provides a historical overview of the significant public health contribution of U.S. municipal drinking water chlorination and its explosive growth (p. 257):
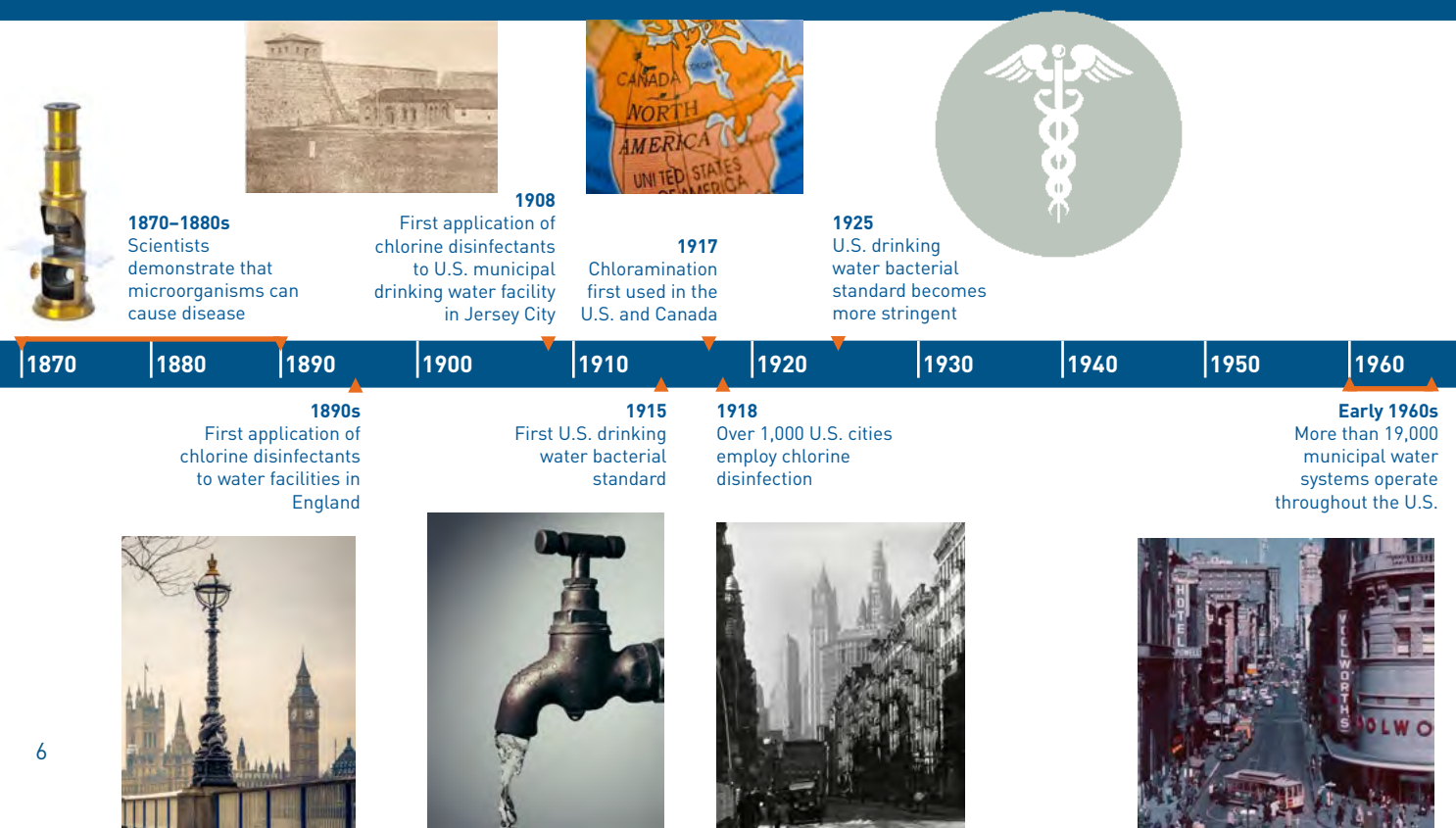
Jersey City was the only utility using chlorine in 1908, but by 1914, more than 21 million people were receiving water from chlorinated municipal supplies . . . In 1918, it was estimated that 3,000 million gallons per day (mgd) were being treated with chlorine in more than 1,000 North American cities.

It took the addition of less than one part per million (ppm or mg/L) of chlorine to municipal drinking water supplies to virtually eliminate waterborne typhoid fever in the United States.

Figure 1-1 shows the rapid decline in the death rate due to typhoid fever following the introduction of chlorine to U.S. drinking water systems beginning in 1908. As cities increasingly adopted water chlorination, death rates due to waterborne disease declined dramatically. Worldwide, significant improvements in public health and quality of life are directly linked to the widespread adoption of drinking water filtration and chlorination. Recognizing this success, *Life* magazine (Anonymous, 1997) declared, "The filtration of drinking water plus the use of chlorine is probably the most significant public health advancement of the millennium."

Box 1-1: CHLORINATION AND WATER QUALITY MILESTONES

1870–1880s Scientists demonstrate that microorganisms can cause disease

1908 First application of chlorine disinfectants to U.S. municipal drinking water facility in Jersey City

1917 Chloramination first used in the U.S. and Canada

1925 U.S. drinking water bacterial standard becomes more stringent

1870 | 1880 | 1890 | 1900 | 1910 | 1920 | 1930 | 1940 | 1950 | 1960

1890s First application of chlorine disinfectants to water facilities in England

1915 First U.S. drinking water bacterial standard

1918 Over 1,000 U.S. cities employ chlorine disinfection

Early 1960s More than 19,000 municipal water systems operate throughout the U.S.
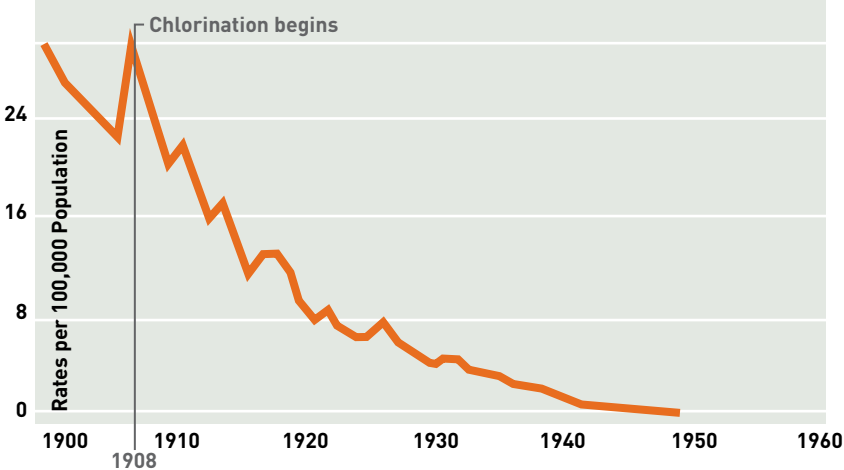
The timeline at the bottom of these pages highlights important developments in the history of U.S. drinking water chlorination and regulation.

Providing Safe Drinking Water: A Multi-Barrier Approach

Meeting the goal of clean, safe drinking water requires a multi-barrier approach that includes protecting raw source water from contamination, appropriately treating raw water, and ensuring safe distribution of treated water to consumers' taps.

Source Water Protection   Source water includes any surface water (rivers and lakes) or groundwater used as a raw water supply. Every drop of rain and melted flake of snow that does not re-enter the atmosphere after falling to the ground wends its way, by the constant pull of gravity, into the vast interconnected system of Earth's surface and groundwaters.

Figure 1-1: Historical Death Rates for Typhoid Fever in the United States

Chlorination begins

Rates per 100,000 Population

24

16

8

0

1900 1910 1920 1930 1940 1950 1960

1908

Source: CDC,1997.

1972
Passage of U.S. Clean Water Act for restoring and maintaining surface water quality

1996
Safe Drinking Water Act Amendments extended to recognize: source water protection, operator training, funding for water system improvements, and enhanced public information

2005
EPA's Stage 2 Disinfectants and Disinfection Byproducts Rule developed to further reduce consumer exposure to disinfection byproducts

2008
100th Anniversary of the first continuous use of chlorine disinfectant in a U.S. municipal drinking water facility (Jersey City)

2013
Michael J. McGuire publishes *The Chlorine Revolution: Water Disinfection and the Fight to Save Lives*, documenting the public health history of U.S. drinking water chlorination

1970 1980 1990 2000 2010 2015 2018

1974
Passage of U.S. Safe Drinking Water Act: The U.S. Environmental Protection Agency (EPA) is given authority to set water quality standards, which states must enforce

1989
EPA's Total Coliform Rule developed to protect against fecal contamination of water

2001
EPA's Stage 1 Disinfectants and Disinfection Byproducts Rule developed to reduce consumer exposure to disinfection byproducts

2006
EPA's Long Term 2 Enhanced Surface Water Treatment Rule developed to reduce exposure to *Cryptosporidium* and other pathogens in surface water sources

EPA's Ground Water Rule developed, establishing a risk-based approach to target ground water systems that are vulnerable to fecal contamination

2013
EPA's Revised Total Coliform Rule developed to reduce potential pathways for fecal contamination of drinking water distribution systems

2018
110th Anniversary of the first continuous use of chlorine disinfectant in a U.S. municipal drinking water facility

100 YEARS
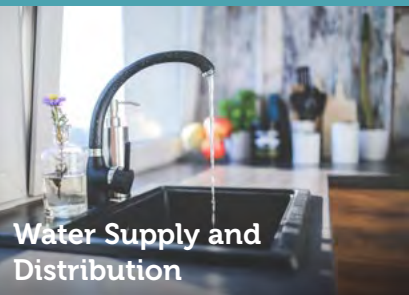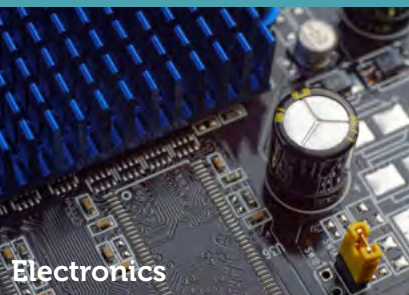
UNITED STATES WATER CHLORINATION
110 YEARS
1908~2018

Precipitation ultimately collects into geographic regions known as watersheds or catchment basins, the shapes of which are determined by an area's topography.

Increasingly, communities are implementing watershed management plans to protect source water from contamination and ecological disruption. For example, vegetated stream buffers called riparian zones may be established as natural boundaries between streams and existing areas of farming, grazing, or development. In addition, land use planning may be employed to minimize the total area of impervious surfaces, such as roads and parking lots, which prevent water from soaking into the ground. Surface waterbodies like reservoirs can be protected from contamination by disinfecting wastewater effluents; prohibiting septic system discharges; limiting combined storm and septic system overflows; repelling birds; and restricting access by cattle, domestic pets, and even wildlife, whose feces can be the source of the harmful protozoan parasites *Giardia* and *Cryptosporidium*.

In 1986, the Safe Drinking Water Act (SDWA) was amended to require states to develop Wellhead Protection Programs for groundwater sources of drinking water. In such programs, the surface region above an aquifer is protected from contaminants that might infiltrate groundwater. Because source water quality affects the drinking water treatment needed, watershed management planning is often considered to be a sustainable, cost-effective step in providing safe drinking water.

Water Treatment   Every day, over 50,000 community water systems treat and convey billions of gallons of treated water to over 300 million Americans (PCAST, 2016). In most basic terms, water is treated to render it suitable for human use and consumption. Although the primary goal is to produce a biologically (disinfected) and chemically safe product, other objectives also must be met, including no objectionable taste or odor, low levels of color and turbidity (cloudiness), and chemical stability (non-corrosive and non-scaling).

Water treatment transforms raw surface and groundwater into safe drinking water. Conventional water treatment involves two types of processes: physical removal of solids (mainly mineral and organic particulate matter) and chemical disinfection (killing/inactivating microorganisms). Individual drinking water systems customize treatment to address the particular natural and man-made contamination characteristics of their raw water supply. Surface water usually presents a greater treatment challenge than groundwater, which is naturally filtered as it percolates through sediments. Surface water is often laden with organic and mineral particulate matter that might harbor parasitic protozoa such as chlorine-resistant *Cryptosporidium*.

Figure 1-2 illustrates drinking water treatment fundamentals. Although practices vary from facility to facility, there are four generally accepted basic processes—as well as treated water storage and distribution—included in conventional drinking water treatment.

## Figure 1-2: Drinking Water Treatment Fundamentals

1. Coagulation and Flocculation remove dirt and other particles and some natural organics in the raw water. Alum (an aluminum sulfate) or other metal salts are added to raw water to form coagulated sticky masses called floc that attract other particles. Their combined weight causes the floc to sink during subsequent mixing and sedimentation.

2. Sedimentation of coagulated, heavy particles through gravity to the bottom of the solids settling basin.

3. Filtration of water from the sedimentation tank is accomplished by forcing water through sand, gravel, coal, activated carbon, or membranes to remove smaller solid particles not previously removed by sedimentation.

4. Disinfection by the addition of chlorine destroys or inactivates microorganisms remaining after the preceding treatment processes. Additional chlorine or chloramine may be applied to ensure an adequate disinfectant residual during storage or transportation throughout the distribution system to homes, schools, and businesses throughout the community.

In **storage** and **distribution**, drinking water must be kept safe from microbial contamination. Frequently, however, biofilms containing microorganisms develop and persist on the inside walls of pipes and storage containers (Falkingham et al., 2015; NRC, 2006). Among disinfection techniques, chlorination is unique in that a pre-determined chlorine concentration may be designed to remain in treated water as a measure of
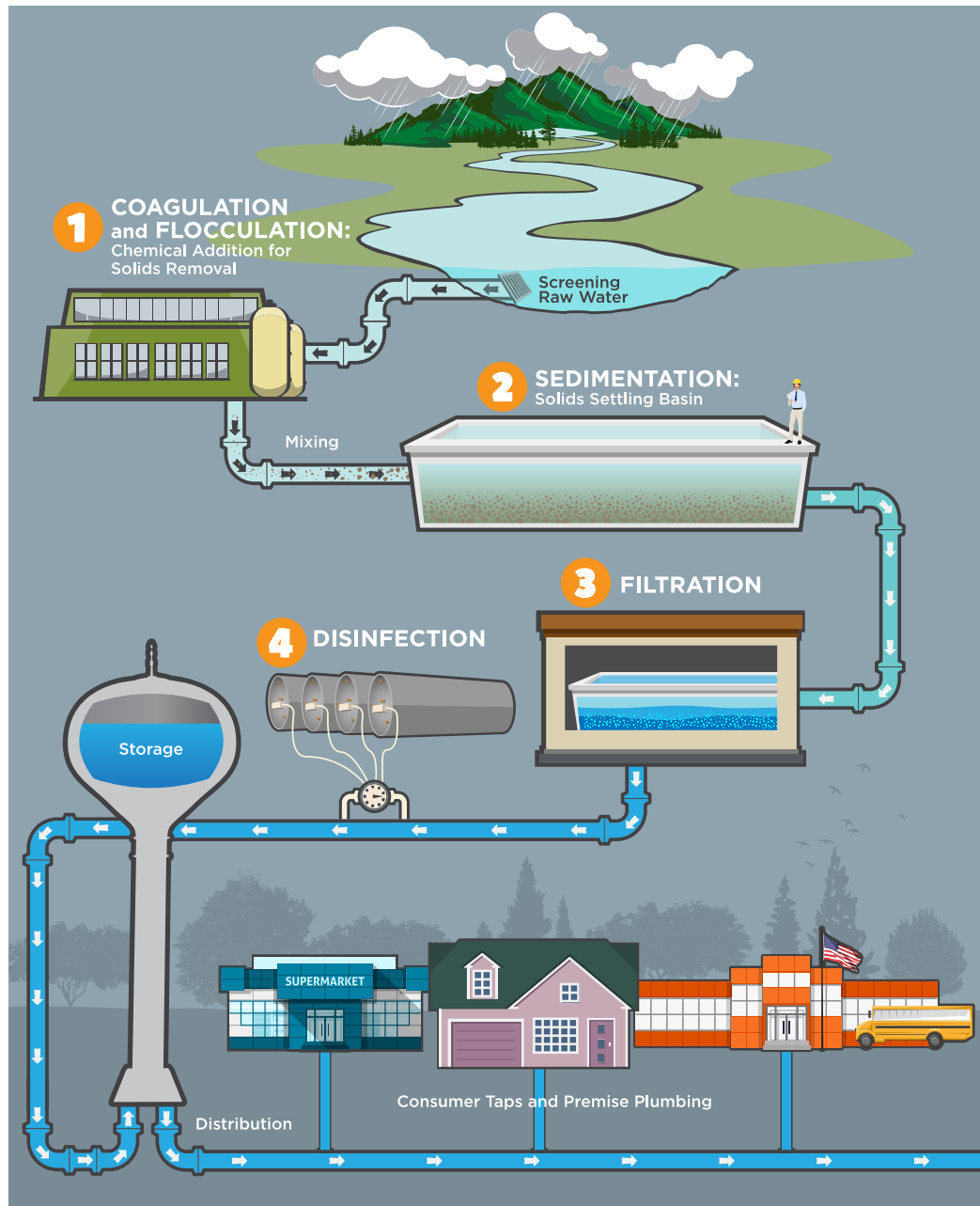
protection against (re)growth of microbes after leaving the drinking water system. In the event of a significant intrusion of pathogens resulting, for example, from a leaking or broken water main, the level of the average chlorine residual will be insufficient to disinfect contaminated water. In such cases, monitoring the sudden drop in the free chlorine residual provides a critical warning to drinking water system operators that there is a source of contamination in the distribution system.

2 Chlorine: The Disinfectant of Choice

Chlorine is added to drinking water to destroy pathogenic (disease-causing) microorganisms. It can be applied in several forms: elemental chlorine (chlorine gas), sodium hypochlorite solution (bleach), and dry calcium hypochlorite.

When applied to water, each of these forms free chlorine (see **Box 2-1**, How Chlorine Kills Pathogens). One pound of elemental chlorine gas provides approximately as much free available chlorine as one gallon of sodium hypochlorite (typically a 12.5% solution) or approximately 1.5 pounds of calcium hypochlorite (65% strength). Although any of these forms of chlorine can effectively disinfect drinking water, each has distinct advantages and limitations for particular treatment applications.

Almost all systems that disinfect their drinking water use some type of chlorine-based disinfection method—either alone or in combination with other chlorine and non-chlorine disinfectants. The recent yet anecdotal results (i.e., 1.4% response rate from over 27,000 community water systems) of the American Water Works Association's 2017 Water Utility Disinfection Survey Report (AWWA, 2018) found that chlorine remains the most widely used (about 70 percent) disinfectant among respondents.

The Benefits of Chlorine Disinfectants

Potent Germicide—Chlorine disinfectants can reduce the level of many disease-causing microorganisms—particularly bacteria and viruses—in drinking water to unmeasurable levels.

Taste and Odor Control—Chlorine disinfectants reduce many disagreeable tastes and odors. Chlorine oxidizes many naturally occurring substances such as foul-smelling sulfides and odors from decaying vegetation.

Biological Growth Control—Chlorine disinfectants help eliminate slime bacteria, molds, and algae that commonly grow in water supply reservoirs, and help control and reduce microorganism-containing biofilms in water distribution systems.

Chemical Control—Chlorine disinfectants react with ammonia and other nitrogenous compounds that have unpleasant tastes and hinder disinfection. They also help to remove iron and manganese from raw water.

Residual Disinfection— Protecting All the Way to the Tap

EPA requires a residual level of disinfection of water in pipelines to prevent microbial (re)growth and help protect treated water throughout the distribution system. EPA's maximum residual disinfection levels are 4 mg/L for chlorine and chloramines, and 0.8 mg/L for chlorine dioxide. Although typical residual chlorine levels are significantly lower in tap water (between 0.2 and 0.5 mg/L) and pose no risk of adverse health effects, allowing for an adequate margin of safety (EPA, 1998), they can produce objectionable taste and odor concerns for some individuals.

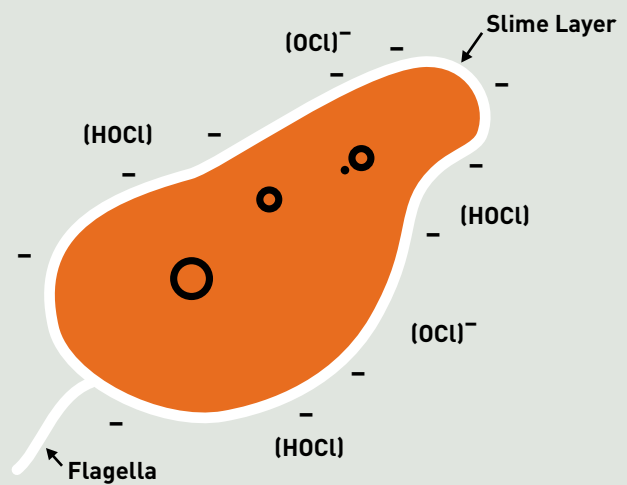## Factors in Chlorine Disinfection: Concentration and Contact Time

To establish more structured operating criteria for water treatment disinfection, the C×T concept came into use in 1980. C×T values—where C is final free chlorine concentration (mg/L) and T is minimum contact time in minutes—offer water

Box 2-1: How Chlorine Kills Pathogens

Drinking water is made microbiologically safe (disinfected) as pathogens either die or are rendered incapable of reproducing (inactivated) so that they cannot infect human hosts. But how does chlorine perform its well-known role of making water safe to drink? Upon adding chlorine to water, two chemical species, collectively called free chlorine, are formed. These species—hypochlorous acid (HOCl, electrically neutral) and hypochlorite ion (OCl⁻, electrically negative)—behave very differently. Hypochlorous acid is not only more reactive than the hypochlorite ion, but is also a stronger disinfectant and oxidant. Although the hypochlorite ion is less reactive, longer contact times can provide sufficient biocidal activity and disinfection.

The ratio of hypochlorous acid to hypochlorite ion in water is determined by the pH. At low pH (below 7.5), hypochlorous acid dominates while at higher pH (just above neutrality) hypochlorite ion dominates. Thus, the speed and efficacy of chlorine disinfection can be affected by the pH of the water being treated. Fortunately, bacteria and viruses are relatively susceptible to chlorination over a wide range of pH. However, treatment operators of surface water systems treating raw water contaminated by the chlorination-resistant *Giardia* often take advantage of the pH-hypochlorous acid relationship and decrease the pH to help ensure that the protozoan parasite is eliminated. Treatment operators may also maintain low pH because viruses and bacteria are more susceptible to disinfection by chlorine at these lower pHs. *Cryptospordium*, a protozoan parasite, is not affected by conventional drinking water chlorination and must be specifically filtered or inactivated through ultraviolet radiation.

Another reason for maintaining a predominance of hypochlorous acid during drinking water treatment is because bacterial pathogen surfaces typically carry a natural negative electrical charge and thus are more readily penetrated by the uncharged, electrically neutral hypochlorous acid than negatively charged hypochlorite ions.

Source: Adapted from Cornell, 1996.

treatment operators guidance in determining an effective combination of chlorine concentration and contact time required to achieve disinfection of water at a given temperature. If an operator chooses to decrease the chlorine concentration, the required contact time must be lengthened. Conversely, as higher strength sodium hypochlorite solutions are used, contact times can be reduced (Connell, 1996).

3 The Risks of Waterborne Disease

It is easy to take for granted the safety of modern drinking water treatment systems, but prior to widespread filtration and chlorination, contaminated drinking water presented a significant public health risk. The microscopic waterborne agents of cholera, typhoid fever, dysentery, and hepatitis A killed thousands of U.S. residents annually before chlorine disinfection methods were increasingly employed beginning over a century ago in Jersey City, New Jersey (McGuire, 2013). Although these and other pathogens are now controlled routinely, they should be considered as ever-ready to reappear wherever there is a break-down in the multi-barrier approach to safe drinking water provision—especially insufficient chlorine disinfection within treatment plants or their storage and distribution systems.

Illnesses Associated with Waterborne Pathogens

Globally, at least 2 billion people use a fecally-contaminated drinking water source, which can transmit both chronic (endemic) and acute (outbreak) diseases such diarrhea, cholera, dysentery, typhoid fever, and polio (WHO, 2017). Contaminated drinking water is estimated to cause over 500,000 diarrheal deaths each year, mostly among children (WHO, 2018a). Many important waterborne and emerging diseases are zoonotic—caused by pathogens that can spread between animals and humans under natural conditions—with wildlife often serving as an important reservoir.

Drinking water pathogens are generally divided into three main categories: bacteria, viruses, and parasitic protozoa (WHO, 2017). Parasitic helminths (worms) are also significant waterborne pathogens in many developing areas of the world. Bacteria and viruses contaminate both surface water

Vibrio cholerae (Dartmouth College/L. Howard)

and groundwater, whereas protozoa appear predominantly in surface water. The purpose of disinfection is to kill or inactivate microorganisms so that they cannot reproduce and infect human hosts. Bacteria and viruses are well-controlled by normal chlorination; in contrast, protozoa with environmentally-resistant forms might require additional filtration or alternative disinfection (EPA, 2005a).

Bacteria
Bacteria are microorganisms composed of single cells shaped like rods, spheres, or spiral structures. Prior to widespread filtration and chlorination of drinking water, bacteria like *Vibrio cholerae*, *Salmonella typhi*, and several species of *Shigella* routinely caused serious diseases such as cholera, typhoid fever, and dysentery, respectively (McGuire, 2013). In 2000 and 2016, following periods of heavy rainfall, large drinking water outbreaks caused by pathogenic bacteria sickened thousands in Walkerton, Canada, and Havelock North, New Zealand, respectively, when their drinking water supplies were not actively chlorinated (see **Box 3-1** at the end of the chapter). Although developed nations have largely eliminated waterborne bacterial pathogens through the use of chlorine and other disinfectants, the developing world still grapples with these public health enemies (Pandey et al., 2014; WHO, 2017).

Legionella—*Legionella* infection can result in legionellosis, which includes Pontiac fever and Legionnaires' disease. The great majority of people exposed to *Legionella* in outbreak settings develop Pontiac fever—a flu-like illness with no signs of pneumonia. In contrast, Legionnaires' disease is a form of severe pneumonia that can be fatal for susceptible populations, including hospitalized patients, elderly
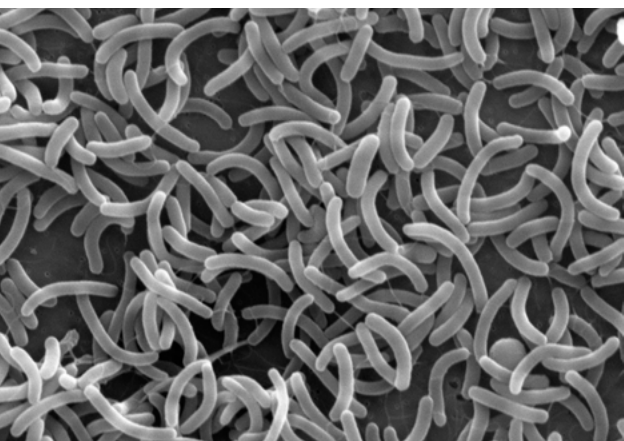
(especially smokers), and people with chronic lung disease or weakened immune systems (Berjeaud et al., 2016). *Legionella* occurs naturally in water and soil and can grow to very high levels in warm water and accumulate in biofilms.

People can become exposed to *Legionella* when they inhale aerosols or mists from contaminated hot tubs, cooling towers, plumbing systems, showers, and decorative pools. Legionnaires' disease is not caused by ingestion of *Legionella*-contaminated water or spread from person to person. *Legionella* are opportunistic pathogens that can persist and grow in household (premise) plumbing—piping that is inside housing, schools, and other buildings. Federal and state regulations as well as local water utilities do not currently require monitoring for *Legionella* within premise plumbing.

CDC (2015, 2017a) recognizes *Legionella* as the most common cause of recent waterborne disease outbreaks in the United States, primarily in hospital and health care environments. From 2013 to 2014, the most recent CDC surveillance period, 57% of 42 reported drinking water-associated outbreaks and all 13 deaths were attributed to *Legionella* bacteria.

Viruses

Viruses are infectious agents that can reproduce only within living host cells. Viruses are so small that they pass through filters that retain bacteria. Enteric viruses, such as hepatitis A, norovirus, and rotavirus, are excreted in the feces of infected individuals and can contaminate water intended for drinking (Gall et al., 2015). Enteric viruses infect the gastrointestinal or respiratory tracts, and are capable of causing a wide range of illness, including diarrhea, fever, hepatitis, paralysis, meningitis, and heart disease. Chlorine is an effective disinfectant for most viruses in drinking water.

Protozoan Parasites

Protozoan parasites are single-celled microorganisms that feed on other microorganisms or multicellular organic tissues and debris. Several species of protozoan parasites are transmitted through water in dormant, environmentally-resistant forms, known as cysts and oocysts (Fletcher et al., 2012). The challenge of the physical removal of cysts and oocysts in the conventional drinking water treatment process is due to their small size. *Cryptosporidium hominis* (formerly *parvum),* *Giardia intestinalis* (formerly *duodenalis* and *lamblia*), and other zoonotic protozoa are introduced to waters all over the world through animal and human fecal pollution (WHO, 2017). The same durable forms that persist in surface waters also make these microorganisms resistant to

conventional drinking water chlorination. Some like *Giardia* can be treated by chlorine at sufficient doses and contact times, but others like *Cryptosporidium* are highly resistant. Treatment plants that properly filter and disinfect raw water can successfully remove or inactivate protozoan parasites.

Cryptosporidium hominis—*Cryptosporidium* is a highly chlorine-resistant zoonotic protozoan pathogen of humans, mammals, and birds that can be potentially life-threatening in immunocompromised patients (Fletcher et al., 2012; Vanathy et al., 2017). It was the cause of the largest reported drinking water outbreak in U.S. history, thought to have affected perhaps over 400,000 people in Milwaukee, Wisconsin, in 1993 with more than 100 deaths.

Cryptosporidium was the second most common cause of U.S. drinking water-associated outbreaks and illnesses from 2013 to 2014 (CDC, 2017a), demonstrating the ongoing public health importance of this chlorine-tolerant parasite.
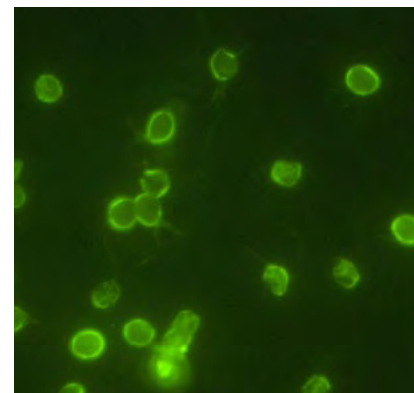
Giardia intestinalis—*Giardia* is a somewhat chlorine-resistant, zoonotic protozoan that can be transmitted to humans through drinking water, but is most commonly transmitted from person to person (Adam et al., 2016; WHO, 2017). However,
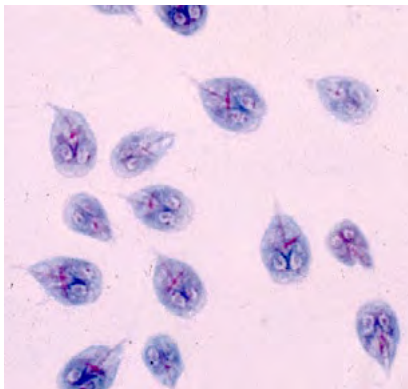
Giardia intestinalis (CDC)

it is now well-recognized that all warm-blooded and some other animals can carry and transmit *Giardia*, which was formerly the most commonly identified cause of U.S. waterborne disease outbreaks. Although some *Giardia* species are also infective to humans, the diarrheal illnesses are usually self-limiting (as is cryptosporidiosis) in healthy people, but are more serious for people with impaired immune systems (Fletcher et al., 2012; WHO, 2017).

Naegleria fowleri—Primary amoebic meningoencephalitis (PAM) is a rare but deadly disease caused by waterborne *Naegleria fowleri*—a naturally-occurring, single-celled protozoan that thrives in soil as well as fresh, warm waters (lakes, rivers, ponds, and hot springs). People enjoying these outdoor venues might be vulnerable when waters containing this organism are forcibly inhaled, as well as people who use neti pots for nasal irrigation. Under these conditions, *Naegleria* can travel along the olfactory nerve to the brain, where it destroys tissue, causes brain swelling, and typically results in death. According to CDC, there were 143 PAM infections in the United States from 1962 through 2017—all but 4 cases were fatal (CDC, 2018). Most infections occur in southern and western states during summer months when temperatures are higher and water levels low. The state of Louisiana has mandated emergency rules in response to

Naegleria detections in drinking water requiring higher disinfectant residual concentrations throughout the affected distribution systems (WQHC, 2015a).

Algae
Algal and cyanobacteria (also called blue-green algae) blooms are typically associated with solar exposure in slow-moving waters that have high nutrient loadings (CDC, 2017b). Although algae and cyanobacteria are not waterborne pathogens per se, one or more toxins like microcystin-LR are produced by some blooms, which are generally referred to as harmful algal blooms. Free chlorine and some other oxidants can be used in drinking water treatment plants to chemically react with and denature many of the toxins and to reduce human exposure. Chlorine and ozone can also lyse (destroy by rupturing) algal cells, but because this can also release cellular toxins, a best practice for controlling algal blooms and toxins is to (1) remove the cells by filtration prior to chlorine addition, and (2) maintain a free chlorine residual throughout the distribution system. Algal blooms also produce objectionable taste and odor substances, such as geosmin and 2-methylisoborneol, which can be exacerbated with chlorine—another reason to maximize algae cell removal before chlorination. Powdered or granular activated carbon addition before filtration along with potassium permanganate can also be used to enhance algal toxin control.
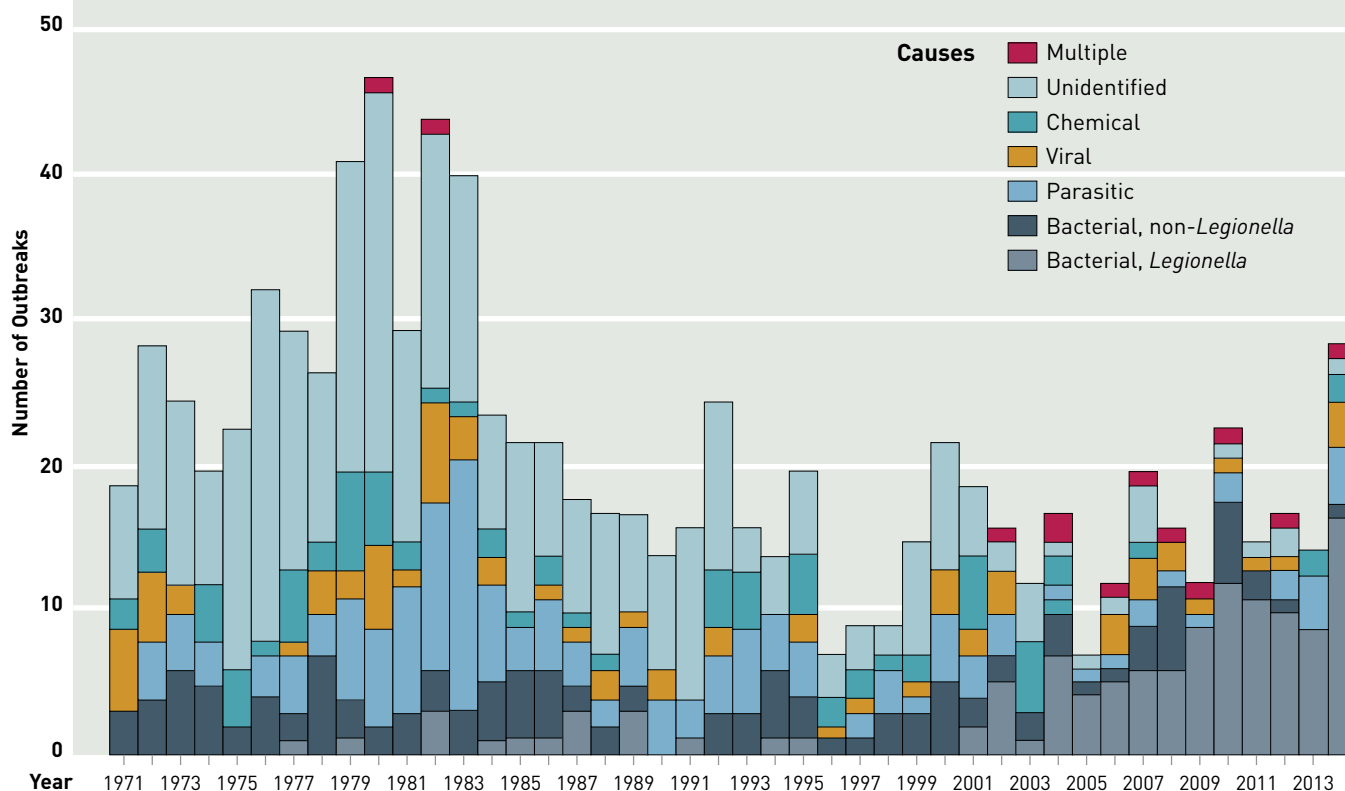
Select EPA Rules to Control Waterborne Disease

Long Term 2 Enhanced Surface Water Treatment Rule—EPA has developed regulations to address the health effects and reduce the risks associated with *Cryptosporidium* and other chlorination-resistant

pathogens in surface water used as a drinking water supply. Key provisions of EPA's LT2 Rule (EPA, 2005a) build on EPA's Long Term 1 Enhanced Surface Water Treatment (LT1) Rule (EPA, 2002) and address surface water and groundwaters under the influence of surface waters. These include: source water monitoring for *Cryptosporidium*, dual disinfectant inactivation by unfiltered systems, and potentially additional treatment for filtered systems based on source water *Cryptosporidium* concentrations (EPA, 2005a). Almost all surface water systems achieve compliance with their conventional treatment processes by maintaining turbidities below 0.3 NTU (Nephelometric Turbidity Units). EPA provides a range of treatment options to achieve the inactivation requirements. Systems with high concentrations of *Cryptosporidium* in their source water may incorporate additional treatment or filtration processes, including alternative disinfection methods (e.g., ozone, UV radiation, chlorine dioxide). However, most treatment plants are expected to meet EPA requirements while continuing to use chlorination. Regardless of the primary disinfection method used, treatment plants must continue to maintain residual chlorine level disinfectants in their distribution systems.

Ground Water Rule—EPA's final Ground Water Rule was promulgated in 2006 to reduce the risk of exposure to fecal contamination that might be present in groundwater drinking sources. The rule establishes a risk-targeted strategy to identify drinking water sources that are at high risk for contamination by screening for detection of indicator organisms and viruses. The Ground Water Rule also specifies when corrective action, including chlorine disinfection, is required to protect consumers from bacteria

Figure 3-1: Causes of 928 Reported U.S. Drinking Water-Associated Outbreaks, by Year
Based on 1971–2014 CDC Data*

Causes
- Multiple
- Unidentified
- Chemical
- Viral
- Parasitic
- Bacterial, non-*Legionella*
- Bacterial, *Legionella*

* Legionellosis outbreaks were first reported to CDC's Waterborne Disease and Outbreak Surveillance System in 2001; Legionellosis outbreaks before 2001 were added retrospectively during the 2007–2008 reporting period.

Source: Adapted from CDC, 2017a.

and viruses (EPA, 2006a).

Revised Total Coliform Rule—EPA's 2013 Revised Total Coliform Rule (RTCR) modified the existing rule by eliminating the maximum contaminant level (MCL) for total coliforms—a group of enteric bacteria, including *E. coli*, which indicate both the presence of fecal contamination and the effectiveness of water treatment (NRC, 2004). The RTCR established an MCL for *E. coli*, and uses *E. coli* and total coliforms to initiate a targeted ("find and fix") approach for addressing fecal contamination that could enter into a distribution system. Similar to the original Total Coliform Rule, it requires all public drinking water systems to (1) perform monitoring based upon system

size; (2) follow-up on detections to determine the cause; and (3) identify sanitary defects and subsequently take action to correct them (EPA, 2013).

Waterborne Disease Trends

Detection and investigation of waterborne disease outbreaks is the primary responsibility of local, state, and territorial public health departments with voluntary reporting to CDC's Waterborne Disease and Outbreak Surveillance System (WBDOSS). CDC and EPA collaborate to track waterborne disease outbreaks of both microbial and chemical origin. Data on drinking water-related contamination have been collected and summarized since 1971 (2001 for *Legionella*

bacteria), but it is important to note that many waterborne disease outbreaks are neither detected nor reported. Despite these limitations, the CDC database is the best available and most comprehensive information source for U.S. outbreaks.

The tables and figures that follow are based on the most recent WBDOSS data (CDC, 2017a). **Figure 3-1** shows the number of drinking water-associated outbreaks in the U.S. from 1971 to 2014. As can be seen, the number of reported outbreaks peaked in 1980, but has generally decreased over time, while *Legionella*-related outbreaks have increased.

Table 3-1 displays CDC WBDOSS data for reported outbreaks and

Table 3-1: Ranked Order of 42 Reported U.S. Waterborne Disease Outbreaks and 1,006 Cases by Water System Type, Water Source, Predominant Illness, and Deficiencies from 2013–2014

Characteristic	Rank	Outbreaks			Cases		
		Category	No.	%	Category	No.	%
Water system type[a]							
	1	Community	30	71.4	Community	759	75.4
	2	Noncommunity	5	11.9	Individual	124	12.3
	3	Individual	3	7.1	Noncommunity	115	11.4
	4	Unknown	3	7.1	Unknown	6	0.6
	5	Bottled	1	2.4	Bottled	2	0.2
Water source							
	1	Groundwater	14	33.3	Surface water	795	79.0
	2	Surface water	14	33.3	Groundwater	157	15.6
	3	Unknown	12	28.6	Unknown	39	3.9
	4	Mixed[b]	1	3.1	Mixed[b]	12	1.2
	5	Unreported	1	3.1	Unreported	3	0.3
Predominant illness[c]							
	1	Acute respiratory illness	24	57.1	Acute gastrointestinal illness	862	85.7
	2	Acute gastrointestinal illness	17	40.5	Acute respiratory illness	130	12.9
	3	Acute gastrointestinal illness; neurologic illness	1	2.4	Acute gastrointestinal illness; neurologic illness	14	1.4
Deficiency[d]							
	1	*Legionella* in drinking water system	23	54.8	Treatment not expected to remove contamination	485	48.2
	2	Unknown/insufficient information	7	16.7	Unknown/insufficient information	143	14.2
	3	Multiple	3	7.1	*Legionella* in drinking water system	126	12.5
	4	Treatment not expected to remove contamination	3	7.1	Treatment deficiency	119	11.8
	5	Untreated groundwater	3	7.1	Untreated groundwater	70	7.0
	6	Distribution system	1	2.4	Multiple	42	4.2
	7	Premise plumbing system	1	2.4	Premise plumbing system	14	1.4
	8	Treatment deficiency	1	2.4	Distribution system	7	0.7

a Community and noncommunity water systems that have ≥15 service connections or serve an average of ≥25 residents for ≥60 days a year. Community water systems serve year-round residents of a community, subdivision, or mobile home park. Noncommunity water systems serve an institution, industry, camp, park, hotel, or business for only part of a given year.

b Includes outbreaks with mixed water sources (groundwater and surface water).

c The category of illness reported by ≥50% of ill respondents; all legionellosis outbreaks were categorized as acute respiratory illness.

d Outbreaks are assigned one or more deficiency classifications per CDC (2016).

Source: Adapted from CDC, 2017a.

cases of illness from 2013 to 2014. The most commonly identified deficiency leading to drinking water-associated disease was *Legionella* in premise plumbing systems (55%).

Not included in the preceding table, but also an important finding from the CDC database, was that waterborne illnesses killed 13 people and

caused 124 hospitalizations during 2013 and 2014. All of the outbreak-associated deaths and all of the outbreaks reported in health care settings were caused by *Legionella* bacteria (CDC, 2017a).

Further, as indicated in **Figure 3-2**, *Legionella* was responsible for 57% of all 2013 and 2014 reported outbreaks

(making acute respiratory illness the most commonly reported outbreak illness type) and 13% of all illness cases. These data point to the importance of ongoing efforts to improve *Legionella* monitoring, mitigation, and risk communication for building water systems—particularly in health care and related facilities. Figure

Figure 3-2: Reported U.S. Waterborne Disease Outbreaks, Cases of Illness, and Causes
Based on 2013–2014 CDC Data

42 Disease Outbreaks

- 57%
- 19%
- 10%
- 7%
- 2%
- 2%
- 2%

1,006 Cases of Illness

- 50%
- 29%
- 13%
- 7%
- 1%
- 0%
- 0%

Causes
- Multiple
- Unknown
- Chemical
- Viral
- Parasitic
- Bacterial, non-*Legionella*
- Bacterial, *Legionella*
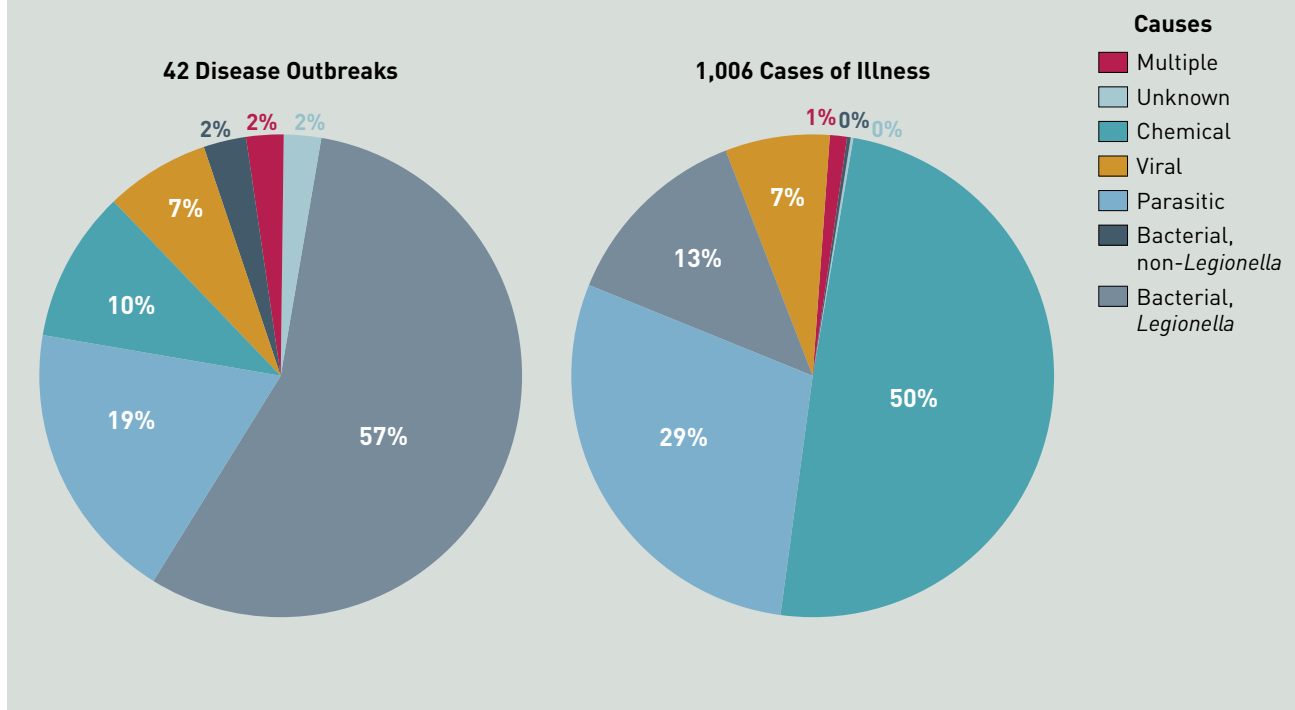
Source: Adapted from CDC, 2017a.

3-2 also shows that chemicals/toxins, viruses, and parasites (mostly *Cryptosporidium*) accounted for 86% of reported cases of illness, even though they only caused 36% of total reported waterborne disease outbreaks. Of the total cases of illness, 369 were attributed to a large spill of a coal cleaning chemical into a river in West Virginia in 2014. Collectively, the outbreak data highlight the importance of drinking water system performance monitoring, ensuring adequate chlorine disinfection within treatment facilities, and maintaining sufficient residual chlorine levels throughout distribution systems at all times. Indeed, CDC (2017a; p. 1216) emphasizes:

Effective water treatment and regulations can protect public drinking water supplies in the United States, and rapid detection, identification of the cause, and

response to illness reports can reduce the transmission of infectious pathogens and harmful chemicals and toxins.

Box 3-1: Outbreaks in Walkerton, Canada, and Havelock North, New Zealand

Insufficient drinking water chlorination led to tragedy in the small Ontario town of Walkerton in the spring of 2000. According to a report published by the Ontario Ministry of the Attorney General (2002), for years the town's public utility commission operators failed to follow established Canadian Ministry of the Environment guidelines on chlorine dosing, monitoring and recording chlorine residuals, and documenting periodic microbiological sampling. The report states that the operators knew their practices were "unacceptable and contrary to Canadian Ministry of the Environment guidelines and directives."

Following several days of unusually heavy rainfall in early May of 2000, manure, applied as fertilizer to farm soil, leaked into one of the town's nearby municipal wells. Untreated pathogenic bacteria in the manure contaminated the well water because the well's chlorinator was not operating due to inadequate maintenance. As the contaminated water from that well blended into the general water supply, the existing free chlorine levels were overwhelmed by the sudden influx of organic matter and bacteria. Before long, schools emptied and emergency rooms filled with children and elderly patients suffering from diarrhea and other gastrointestinal symptoms. By the time the cause of the symptoms was traced to contamination of the town's municipal water supply, many of the town's residents were already very ill. DNA typing studies performed later would reveal pathogenic *E. coli* O157:H7 and *Campylobacter jejuni* and that bacterial strains present in the manure matched those that were prevalent in the human outbreak. The outbreak left 7 people dead and an estimated 2,300 ill.

Conclusions from the comprehensive 2002 report state that the Walkerton outbreak could have been prevented "by the use of continuous chlorine residual and turbidity monitors . . ." By failing to properly monitor chlorine residual levels, the water operators permitted the town water's chlorine concentration to plummet, setting the stage for a major outbreak of waterborne disease.

In August 2016, a series of events that proved to be highly similar to the Walkerton outbreak unfolded in Havelock North, a suburb of the City of Hastings on the North Island of New Zealand. By the end of the month, over one-third of the town's 14,000 residents had been sickened by drinking water contaminated with *Campylobacter* bacteria, which was eventually associated with up to 4 deaths.

Just days before the first people became sick, the region received three months' worth of rain in a single weekend. Unlike the Walkerton outbreak, Havelock North was intentionally not chlorinating because their groundwater had been considered "secure" from contamination. The Government Inquiry into Havelock North Drinking Water (2017a) found that untreated contaminated drinking water was the source of the *Campylobacter* that sickened thousands. Further, sheep feces were the likely source of the bacteria, which were washed into a farm pond, entered the aquifer, and subsequently pumped into a nearby public well serving the community.

The two-stage outbreak investigation raised concerns about the management of public water sources across New Zealand, including whether chlorination should be required for all community drinking water supplies (Government Inquiry into Havelock North Drinking Water, 2017b). Both outbreaks should serve as cautionary tales: Public health officials must be ever vigilant to safeguard drinking water sources from contamination while ensuring appropriate disinfection.

4 The Challenge of Disinfection Byproducts

Since its inception in the United States in 1908, drinking water chlorination has been a major reason for both the dramatic decline in waterborne disease rates and increased life expectancy. Largely because of this success, most Americans take it for granted that their tap water will be free of disease-causing microorganisms (McGuire, 2013).

In recent years, regulators and the general public have focused greater attention on potential health risks from chemical contaminants in drinking water. One such concern relates to disinfection byproducts (DBPs)—very low concentrations of complex mixtures of chemical compounds formed unintentionally when chlorine and other disinfectants react with naturally-occurring organic matter in water.

Although the available evidence from decades of study (and debate) has not established a causal relationship between DBPs in drinking water and potential adverse health effects in humans, high levels of these chemicals are undesirable. Cost-effective methods to reduce DBP formation are available and are required by regulation in many countries. However, the *WHO Guidelines for Drinking-water Quality* (WHO, 2017; p. 173) strongly caution:

In attempting to control DBP concentrations, it is of paramount importance that the efficiency of disinfection is not compromised and that a suitable residual level of disinfectant is maintained throughout the distribution system.

In the early 1970s, John Rook, a Dutch brewery chemist, and EPA scientists, independently determined that drinking water chlorination could form a group of byproducts known as trihalomethanes (THMs), including (1) chloroform, (2) bromodichloromethane (BDCM), (3) dibromochloromethane (DBCM), and (4) tribromomethane (bromoform). The sum of chloroform, BDCM, DBCM, and TBM concentrations is referred to as total trihalomethanes or TTHM. Based upon limited data, but concern that these chemicals might be carcinogenic to humans, EPA set the first regulatory limits for TTHM in 1979 with its Total Trihalomethane Rule. Since that time, a wealth of research has improved our understanding of THMs, haloacetic acids (HAAs), and other DBPs. Although all chemical disinfectants are known to form byproducts, the DBPs of chlorine disinfection of water are by far the most thoroughly studied (see Hrudey et al., 2015; Li and Mitch, 2018).

The carcinogenicity of THMs is now questioned, but EPA's TTHM and HAA5 (monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, bromoacetic acid, and dibromoacetic acid) water quality standards can be considered as group indicators for the presence of other DBPs that are concurrently produced (EPA, 2015; Li and Mitch, 2018; WRF, 2017a). Measures to reduce regulated DBPs should also reduce most other (unregulated) DBPs. This is analogous to the historic and ongoing use of generally harmless coliform bacteria as indicators for fecal pathogens and the effectiveness of water treatment (NRC, 2004). EPA's TTHM and HAA5 standards can also be considered as drivers of treatment technologies that will also reduce many other DBPs.

The original EPA TTHM MCL was 100 parts per billion (ppb) (100 µg/L). The current TTHM MCL is 80 ppb. It is important to emphasize that the current (2017) WHO Guidelines consider chloroform and most other THMs to be non-carcinogens or "threshold carcinogens" at drinking water occurrence levels. That

is, the weight of evidence indicates that chloroform is not genotoxic and does not damage or cause mutations to DNA at drinking water concentrations.

Most U.S. water systems are meeting EPA's TTHM and HAA5 standards by controlling the amount of naturally-occurring organic matter prior to disinfection; many others are using monochloramine as a secondary disinfectant (in the distribution system) to reduce DBP formation (see Chapter 6 and WRF, 2017a). Ensuring microbial protection remains the top priority. Monochloramines are produced by reacting chlorine and ammonia.

Disinfection Byproduct Science and Regulations/Guidelines

While early studies reported that high doses of THMs in laboratory animals fed corn oil caused cancer in laboratory animals, later studies using drinking water did not support these findings. EPA had considered most individual THMs and HAAs to be either possible or probable human carcinogens, although any risk from the low levels typically found in drinking water would be slight. After reviewing the full body of health effect studies, the WHO's International Programme on Chemical Safety (IPCS, 2000; p. 376) concluded

None of the chlorination disinfection by-products studied to date is a potent carcinogen at concentrations normally found in drinking water.

Table 4-1 summarizes current International Agency for Research on Cancer (IARC) designations for individual THM compounds and corresponding current WHO drinking-water guidelines and EPA maximum contaminant level goals (MCLGs).

Epidemiology

TTHM regulations in the United

Table 4-1: Summary of THM Compound IARC Designations, WHO Drinking-Water Guidelines, and EPA MCLGs

THM	IARC Designation	WHO Guideline (ppb)	EPA MCLG (ppb)
Chloroform	2B	300	70
DBCM	3	100	60
BDCM	2B	60	Zero
Bromoform	3	100	Zero

Group 2B = Possibly carcinogenic to humans. Group 3 = Not classifiable as to its carcinogenicity to humans. *Source: EPA, 2018; WHO, 2017.*

States have been in effect for almost 40 years and TTHM and other DBP exposures from drinking water have been substantially reduced over time. Many drinking water treatment facilities have converted from free chlorine to chloramine residuals to help meet more stringent EPA DBP rules (WRF, 2017b).

Some epidemiology studies have reported an association between chlorinated drinking water and slightly elevated risks of certain cancers, while other studies have found no association (Hrudey et al., 2015; Li and Mitch, 2018).

EPA (2005a, 2016) evaluated the existing cancer epidemiology studies and found that only for bladder cancer were associations with chlorinated water somewhat consistent, although bladder cancer is known to be strongly associated with smoking, age, and exposure to certain industrial chemicals (Hrudey et al., 2015). Even in positive studies, cancer risks were relatively small and not consistently correlated to measured TTHM levels, indicating that other (confounding) factors cannot be ruled out (Craun et al., 2001).

EPA's most recent Six-Year Review of Drinking Water Standards concluded (EPA, 2016; p. 4-31) "a causal relationship has not yet been established between bladder cancer and exposure to any individual DBP or combinations of DBPs (oral, dermal,

inhalation) as noted by others." This finding remains consistent with an earlier IPCS (2000) conclusion that a causal relationship between DBPs and increased cancer remains an open question.

Developmental and Reproductive Effects

Several correlational epidemiology studies have reported a possible association between DBPs and adverse reproductive outcomes, including spontaneous abortion (miscarriage) (see EPA, 2016).

After reviewing all available epidemiological studies in support of the 2006 Stage 2 DBP Rule, EPA (2005b) did not change the TTHM or HAA5 MCLs; however, they were listed as candidates for revision following EPA's (2016) Six-Year Review of Drinking Water Standards.

Updating the Safe Drinking Water Act Regulations

EPA has regulated DBPs in drinking water since the Total Trihalomethane Rule established an MCL of 100 ppb for TTHM in 1979 (EPA, 2015).

EPA's Stage 1 Disinfectants and Disinfection Byproduct Rule

In 1998, the Stage 1 DBP Rule was established that lowered the TTHM MCL to 80 ppb (EPA, 1998, 2001a). It also established new TTHM MCL standards and a treatment technique of enhanced coagulation and enhanced softening to reduce

natural DBP precursors and further reduce DBP exposure. The MCL applied to all systems that added chlorine, chloramine, or chlorine dioxide as a disinfectant. For the original 1979 Total Trihalomethane Rule and the Stage 1 DBP Rule, compliance was determined by averaging all samples in specific locations in the distribution system.

In addition to lowering the TTHM MCL level, the Stage 1 DBP Rule set enforceable MCLs for HAA5 at 60 ppb, chlorite at 100 ppb (for plants that use chlorine dioxide disinfectant), and bromate at 10 ppb (for plants that disinfect with ozone) (see EPA, 2010). The TTHM and HAA5 MCLs were based on distribution system running annual averages, meaning that concentrations could exceed the MCL at certain times and at certain locations throughout the distribution system, but as long as the average concentration for the year was below the MCL, the water system was in compliance with the Stage 1 DBP Rule.

In developing the Stage 1 DBP Rule in the late 1990s, EPA was cautious about encouraging the use of alternative disinfectants. The Agency recognized that alternative disinfectants might reduce TTHM and HAA5, but produce other, less understood, byproducts. The Agency also avoided making recommendations that would encourage utilities, especially small systems, to reduce the level of disinfection currently being practiced.

EPA's Stage 2 Disinfectants and Disinfection Byproduct Rule
A Stage 2 DBP Rule was promulgated in 2006, which supplements EPA's 1998 Stage 1 DBP Rule (EPA, 2006b). The Stage 2 DBP Rule is intended to reduce DBP exposures by limiting exposure to TTHM and HAA5. It requires treatment plants that add chlorine, chloramine, or

chlorine dioxide as a disinfectant to comply with the same TTHM (80 ppb) and HAA5 (60 ppb) MCLs, but changes how compliance with the MCLs is calculated (EPA, 2005a). Because DBP formation increases over time, "older water" in the more distant portions of the distribution system tend to have higher levels of DBPs than locations closer to the treatment plant. The Stage 2 DBP Rule established more stringent MCL requirements by calculating "locational running annual averages," which are annual averages for each sampling location (as opposed to the entire distribution system average used in the Stage 1 DBP Rule) (see EPA, 2010). The more stringent averaging requirements increase the probability of a TTHM and HAA5 MCL exceedance.

Balancing Disinfection Byproducts and Microbial Risks
The 1996 SDWA Amendments required EPA to develop rules to balance the risks between microbial pathogens and DBPs. In maintaining this balance, the WHO's IPCS (2000; p. 375) warned:

Disinfection is unquestionably the most important step in the treatment of water for drinking water supplies. The microbial quality of drinking water should not be compromised because of concern over the potential long-term effects of disinfectants and DBPs. The risk of illness and death resulting from exposure to pathogens in drinking water is very much greater than the risks from disinfectants and DBPs.

Almost two decades later, the WHO's *Drinking-water Guidelines* still emphasize the importance of balancing these risks (WHO, 2017; p. 173):

In attempting to control DBP concentrations, it is of paramount importance that the efficiency of

disinfection is not compromised and that a suitable residual level of disinfectant is maintained throughout the distribution system.

See the Latin American Cholera Epidemic of the 1990s inset (**Box 4-1**) for a poignant example of when a failure to balance these risks had extensive public health ramifications.

The incidence of reported water-borne disease outbreaks in the United States has generally been in decline since the implementation of the SDWA in 1976—due in large part to regulation-driven improved treatment plant operations and oversight by state regulators. However, the proportion of the remaining disease outbreaks due to deficiencies in distribution systems, including plumbing infrastructure, has increased as a result of microbial (re)growth, leaks, main breaks, and decaying pipes. Such deficiencies can cause a drop in residual chlorine levels and increase microbial pathogen risks. As noted previously, *Legionella* is now considered to be the most significant drinking water-related disease risk, and is caused by inhalation of contaminated water aerosols from premise plumbing, spas, and cooling towers (CDC, 2017a).

Controlling Disinfection Byproducts
Efficient and cost-effective treatment techniques are available that provide drinking water suppliers the opportunity to maximize potable water safety and quality while minimizing any potential DBP risks. Such DBP control strategies can be divided into three categories: (1) removal of DBP precursors, (2) optimization of treatment and disinfection practices to minimize DBP formation, and (3) removal of DBPs after formation (WRF, 2017c). In general, maintaining THM and HAA concentrations below regulatory or

Box 4-1: The Latin American Cholera Epidemic of the 1990s

Between 1991 and 1993, cholera, an acute and deadly diarrheal disease, raged throughout Latin American, sparing only Uruguay and the Caribbean. The outbreak claimed almost 9,000 lives and sickened nearly one million people [Guthman, 1995].

For many years prior to 1991, the Pan American Health Organization (PAHO) had been promoting the disinfection of community water distribution systems. Primarily through its Center for Sanitary Engineering and Environmental Science in Lima, Peru, PAHO collaborated with the countries in demonstration and pilot projects for virtually all disinfection methodologies to ascertain their relative efficiency, cost effectiveness, and practicality for a wide range of cultural and economic situations. Some methods worked well while others were failures. Chlorination was almost always found to be the most reliable and cost effective.

PAHO's response to the first appearance of cholera was swift. It included a directive to each of the PAHO Country Offices to promote continuous chlorination of all water distribution and delivery systems. Logic guided this decision: chlorine is very effective at destroying the *Vibrio cholerae* pathogen; all of the countries were familiar with chlorination technology; chlorine products were readily available; and chlorination was the least costly disinfection method.

Surprisingly, shortly after the directive to encourage water chlorination, local PAHO officials began encountering pockets of resistance from health officials in Peru and other countries. The resistance stemmed from concern over public exposure to disinfection by-products, a subject highlighted in press releases and published scientific studies widely disseminated by environmental agencies in the developed countries.

It was pointed out to all that when *Vibrio cholerae* is present in a water supply, the risk of contracting the disease is immediate, and that a resulting epidemic could cause thousands of deaths. In contrast, the hypothetical health risk posed by disinfection byproducts at levels in excess of those recommended by the WHO was one extra death per 100,000 persons exposed for a period of 70 years. Unfortunately, some of these well-meaning, but ill-informed officials had to experience the immense proportional difference in risk before accepting this reality.

(Excerpted from "The Latin American Cholera Epidemic of the 1990's: My View from the Inside," by Fred M. Reiff, PE; WQHC, 2015b.)

guideline values by controlling precursor natural organic matter, represented as total organic carbon (TOC), will provide adequate control over other chlorination byproducts (WHO, 2017).

Three treatment processes can effectively remove naturally-occurring organic compounds prior to disinfection (see EPA, 2001b):

1. Coagulation and Clarification
Most drinking water systems optimize their coagulation process for turbidity (particle removal). However, coagulation processes can also be optimized for natural organic matter precursor removal using higher doses of inorganic coagulants (such as alum or iron salts) and optimization of pH.

2. Adsorption
Activated carbon can be used to adsorb naturally-occurring organic substances (TOC) that react with disinfectants to form DBPs. This is, however, costly. Biological activated carbon, which usually involves ozone and granular activated carbon, may be more cost-effective in some instances.

3. Membrane Technology
Advances in membranes, used historically to desalinate briny waters, continue to demonstrate excellent removal of natural organic matter. Membrane processes use hydraulic pressure to force water through a semi-permeable membrane that rejects most contaminants. Variations of this technology include reverse osmosis, nanofiltration (low-pressure reverse osmosis), ultrafiltration, and microfiltration (comparable to conventional sand filtration).

Other conventional DBP control strategies include changing the point of chlorination to later in the treatment process after some of the TOC has been removed (see

Figure 1-2), and using chloramine for residual disinfection, which are much less reactive than free chlorine with DBP precursors. Most U.S. water systems have achieved compliance with updated DBP regulations using one or more of these processes.

Water system managers may also consider switching from chlorine to one or more alternative disinfectants to reduce formation of TTHM and HAA5. However, all disinfectants form some DBPs, many of which remain unknown, while groups of related DBPs (e.g., nitrogenous-DBPs) continue to be identified (WRF, 2017b). Much less is known about the byproducts of disinfectant alternatives to chlorination than is known about chlorination-related DBPs. Moreover, each disinfection method has advantages and disadvantages. Chapter 6 discusses some of the key issues for water system managers to consider when choosing between one or more disinfection methods.

5 Drinking Water and Security

Water treatment and distribution systems provide one of the most basic elements of life—a reliable supply of safe drinking water. Prior to the terrorist attacks of September 11, 2001, for most systems, security measures were primarily designed to protect facilities and equipment from pranks and vandalism. In the post-9/11 reality, protecting and controlling access to these critical systems is now a standard part of water system planning and operations (**Box 5-1**).

Disinfection and Bioterrorism

Disinfection is also crucial to water system security, providing protection against accidental and intentional microbiological contamination. Water systems should maintain the flexibility to increase disinfection doses in response to a particular threat. Normal filtration and disinfection can reduce or remove the threats posed by a number of potential bioterrorism agents. However, even multiple conventional treatment barriers cannot ensure safety from all biological attacks, and for many potential bioterrorism agents, there is limited scientific information regarding achievable levels of reduction that can be achieved with chlorine or other disinfectants.

Protecting Chlorine and Other Treatment Chemicals

Vulnerability assessments provide a comprehensive analysis of potential threats to a drinking water system, including chemical or biological contamination of the water supply and disruption of water treatment or distribution. As part of its vulnerability assessment, each drinking water system should also carefully consider its transportation, storage, and use of treatment chemicals. These chemicals are simultaneously critical assets (necessary for delivering safe water) and potential vulnerabilities (might pose significant hazards, if released). For example, a

release of chlorine gas would pose an immediate threat to system operators, whereas a large release might pose a danger to the surrounding community.

Also as part of its vulnerability assessment, a drinking water system using chlorine should determine whether existing layers of protection are adequate. If not, a system should consider taking additional measures to reduce the likelihood of an attack or to mitigate the potential consequences.

Possible measures to address chlorine security within drinking water treatment systems include enhanced physical barriers (e.g., constructing secure chemical storage facilities); policy changes (e.g., instituting additional secure procedures for receiving chemical shipments); reducing disinfectant quantities stored onsite; or considering the use of alternative disinfection methods, including onsite generation of sodium hypochlorite (see Chapter 6). However, changing disinfection technologies will not necessarily improve overall safety and security as each disinfectant has unique strengths and limitations.

Water system officials should evaluate the risk tradeoffs associated with each option available to address chlorine security. For example, reducing the chemical quantities stored onsite can simultaneously reduce a system's ability to cope with an interruption of chemical supplies. All security-related options should be weighed and prioritized, considering the unique characteristics and resources of each system. In addition, water industry organizations, including AWWA, the Association of Metropolitan Water Agencies, and Association of State Drinking Water Administrators, serve as clearinghouses for sharing security and other critical information with the thousands of drinking water systems located throughout the United States.

Box 5-1: American Water Works Association and American National Standards Institute Security Guidance

For more than 100 years, the AWWA has developed voluntary standards for materials, equipment, and practices used in drinking water treatment and supply. AWWA has worked with the American National Standards Institute (ANSI) to develop guidance documents and voluntary standards related to operational security, risk and resilience management, and emergency preparedness, including the following:

Selecting Disinfectants in a Security-Conscious Environment provides guidance to assist with evaluating disinfectants to meet water quality needs and security considerations. This ANSI/AWWA document helps drinking water system operators analyze and quantify safety and security risks and costs for any type of disinfectant. The information is consistent with the EPA's water utility security guidelines and the Department of Homeland Security (DHS) Chemical Facility Anti-Terrorism Standards (CFATS) Program (AWWA, 2009).

ANSI/AWWA G430-14: Security Practices for Operations and Management Standard provides guidance on developing a protective security program for a water or wastewater utility that will promote employee safety, public health, public safety, and public confidence. This standard received SAFETY (Support Anti-terrorism by Fostering Effective Technologies) Act designation from DHS in 2012, and can apply to all water or wastewater utilities—regardless of size, location, ownership, or regulatory status. The standard builds on the long-standing practice of employing a multi-barrier approach for the protection of public health and safety (AWWA, 2014).

ANSI/AWWA J100-10: RAMCAP Standard for Risk and Resilience Management of Water and Wastewater Systems Standard provides guidance on identifying, analyzing, quantifying, and communicating risks of specific terrorist attacks and natural hazards against critical water and wastewater systems. It also provides guidance on identifying security vulnerabilities and methods to evaluate the options for improving these weaknesses and received SAFETY Act designation from DHS in 2012 (AWWA, 2010).

ANSI/AWWA G440-11: Emergency Preparedness Practices Standard provides guidance for emergency preparedness for a water or wastewater utility. Emergency preparedness practices include the development of an emergency response plan (hazard evaluation, hazard mitigation, response planning and mutual aid agreements, evaluation of the emergency response plan through exercises, and revision of the emergency response plan after exercises) (AWWA, 2011).

6 Comparing Disinfection Methods

Until the late 1970s, chlorine was virtually the only disinfectant used to treat drinking water in the United States. Chlorine was long-considered by treatment operators to be an almost ideal disinfectant because it destroys most pathogens and provides a residual disinfectant to help prevent microbial (re)growth throughout the distribution system. Additionally, chlorine is:

- A potent oxidizer and disinfectant that can detoxify some chemicals
- Suitable for a broad range of water quality conditions
- Easily monitored and controlled
- Cost-effective

Moreover, drinking water providers continue to face new and evolving treatment and regulatory challenges, including:

- Treating chlorine-resistant pathogens such as *Cryptosporidium* and *Giardia*
- Growing *Legionella*, biofilm, and premise plumbing issues
- Minimizing DBP formation and controlling emerging DBPs
- New environmental and safety regulations
- Strengthening security at treatment facilities

To meet these challenges, water system managers must design unique disinfection approaches to match each system's characteristics, source water quality, and resources. Although chlorination still remains the most commonly used disinfection method (AWWA, 2018), drinking water systems increasingly use alternative disinfectants or combinations of disinfectants, including chlorine along with chloramine, chlorine dioxide, ozone, and UV radiation. No single disinfection method is right for all circumstances. Water systems may use a variety of methods as multiple barriers to both

meet overall disinfection goals at the drinking water facility and to provide residual disinfection protection throughout the storage and distribution system.

The sections below summarize and compare conventional and alternative disinfection technologies, and discuss some of the major advantages and limitations associated with each option.

Chlorination

Chlorine is applied to water in one of three principal forms: elemental chlorine (chlorine gas), sodium hypochlorite solution (liquid bleach), or dry calcium hypochlorite. Chlorinated isocyanurates are also used for some drinking water applications (but more commonly for swimming pool disinfection). All produce free chlorine in water (see Box 2-1).

ADVANTAGES

- Highly effective against bacterial and viral waterborne pathogens and some protozoa
- Provides a residual level of disinfectant to help protect against microbial (re)growth and to help control biofilm growth in the distribution system
- Easily applied, controlled, and monitored
- Operationally simple and highly reliable
- The most cost-effective disinfectant

LIMITATIONS

- Disinfection byproduct formation (e.g., THMs, HAAs, and other DBPs)
- Will oxidize bromide in water to hypobromite forming brominated DBPs
- Not effective against *Cryptosporidium*
- Requires transport and storage of chemicals

Elemental Chlorine   Elemental chlorine gas (Cl_2) remains one of the most commonly used form of chlorine in drinking water systems. It is transported and stored as a liquefied gas under pressure. Water treatment facilities typically use chlorine in 100- and 150-pound cylinders or 1-ton containers. Some large drinking water systems use chlorine gas delivered in railroad tank cars or tanker trucks.

ADVANTAGES

- Lowest cost and most energy efficient of all chlorine-based disinfectants
- Unlimited shelf-life
- Does not add bromate
- Will react with algal- and cyano-bacteria-produced toxins

LIMITATIONS

- Hazardous pressurized gas requires special handling and operator training
- Additional regulatory requirements, including EPA's Risk Management Program and the Occupational Safety and Health Administration's Process Safety Management Standard

Sodium Hypochlorite   Sodium hypochlorite, or bleach (an aqueous solution of NaOCl), is produced by adding elemental chlorine to sodium hydroxide. Typically, hypochlorite solutions for water treatment applications contain from 12 to 15% chlorine, and are shipped in 1,000- to 5,000-gallon containers.

ADVANTAGES

- Solution is less hazardous and easier to handle than elemental chlorine (gas)
- Fewer training requirements and regulations than chlorine gas
- Will react with algal- and cyano-bacteria-produced toxins

LIMITATIONS

- Limited shelf-life; degrades slowly over time to chlorate and then perchlorate during storage—particularly at warm temperatures

- Can contain bromate from electrolysis of bromide in the precursor salt

- Corrosive to some materials and more difficult to store than most solution chemicals

- Higher costs than elemental chlorine due to shipping (water) weight (~85%)

Calcium Hypochlorite   Calcium hypochlorite ($Ca(OCl)_2$) is used primarily in small treatment applications. It is a white, dry solid containing approximately 65% chlorine and is commercially available in granular and tablet forms.

ADVANTAGES

- More stable than sodium hypochlorite, allowing longer storage

- Fewer training requirements and regulations than elemental chlorine

- Will react with algal- and cyano-bacteria-produced toxins

LIMITATIONS

- Dry chemical requires more handling than sodium hypochlorite

- Precipitated solids formed in solution complicate chemical feeding

- Higher chemical costs than elemental chlorine

- Fire or explosive hazard if handled improperly

- Can contain chlorate, chlorite, and bromate

Onsite Hypochlorite Generation
In recent years, some municipalities have installed onsite hypochlorite generators that produce weak hypochlorite solutions (~0.8%) using an electrolytic cell and a solution of salt water (brine).

ADVANTAGES

- Storage and transport of salt rather than chlorine gas or sodium hypochlorite solution

LIMITATIONS

- Higher capital and operating cost due to electricity consumption for electrolysis and system maintenance

- More complex processing and requires a higher level of maintenance and technical expertise

- Requires careful control of salt quality

- Weak solution requires high volume chemical feed and control
- Disinfectant backup is required in event of treatment system failure

Chlorine-Based Alternative Disinfectants

Chloramine (Monochloramine)

Chloramines are chemical compounds formed by combining a specific ratio of chlorine and ammonia in water. Monochloramine (NH_2Cl) is the required form; dichloramine and trichloramine are undesirable and ineffective disinfectants, so it is essential to carefully control the blending ratios and process. Because chloramine is a weak disinfectant compared to chlorine, it is almost never used as a primary disinfectant. Chloramine provides a durable residual because it is much less reactive than chlorine gas or sodium hypochlorite. For this reason, it is often used as a secondary disinfectant, particularly for extensive distribution systems. Chloramine reduces chlorinated DBP formation, but also produces different, less well-studied nitrogenous-DBPs, and possibly nitrate and nitrite. It can also be used to minimize some free chlorine-related taste and odor issues.

ADVANTAGES

- Reduced formation of THMs, HAAs, and other chlorinated DBPs
- Will not oxidize bromide to hypo-bromite; therefore, brominated DBPs are not formed
- More stable, lasting residual than free chlorine
- Fewer dose-related taste and odor issues than free chlorine
- Excellent secondary disinfectant; can be potentially more effective than free chlorine at controlling indicator bacteria and biofilms in distribution systems
- Reduces *Legionella* in biofilms and helps protect distributed water

from biofilm-related microorganism activity

LIMITATIONS

- Weaker disinfectant and oxidant than chlorine by several orders of magnitude
- Requires much longer contact times and higher C×T values than free chlorine
- Greater potential to produce nitrosamine and other nitrogenous-DBPs
- Can contribute to nitrification, especially in extended retention distribution systems
- Requires shipment and handling of ammonia or ammonia compounds in addition to chlorinating chemicals
- Ammonia and chloramines are toxic to fish, and can cause problems unless removed, which is more difficult than removing a free chlorine residual
- Must be removed from water used for kidney dialysis
- Will not react with algal- and cyanobacteria-produced toxins

Chlorine Dioxide

Chlorine dioxide (ClO_2) is a gas that is generated onsite at drinking water treatment facilities from sodium chlorite in specially designed generators. One common method of generating chlorine dioxide is by dissolving chlorine gas in water to produce hypochlorous acid and hydrochloric acid, followed by reacting the acids with sodium chlorite.

Chlorine dioxide properties are quite different from free chlorine. In solution, it is a dissolved gas with lower solubility than chlorine. Unlike chlorine, chlorine dioxide does not hydrolyze in water, although it will generate chlorite and chlorate in water; therefore, chlorine dioxide's germicidal activity is relatively constant over a broad range of pH.

Chlorine dioxide is volatile and is easily stripped from solution, and is a strong primary disinfectant and a selective oxidant. Its main inorganic byproducts are chlorite and chlorate. Although chlorine dioxide can produce an adequate residual, it is difficult to maintain, which is why it is rarely used for that purpose.

ADVANTAGES

- Reasonably effective against *Cryptosporidium*
- Up to five times faster than elemental chlorine at inactivating *Giardia*
- Disinfection only slightly affected by pH
- Does not directly form chlorinated DBPs (e.g., THMs, HAAs)
- Does not oxidize bromide to hy-probromite (but can form bromate in sunlight)
- More effective than elemental chlorine in treating some taste and odor problems
- Selective oxidant used for manganese oxidation

LIMITATIONS

- Inorganic DBP formation (chlorite, chlorate)
- Highly volatile residuals
- Requires onsite generation equipment and handling of chemicals (sodium chlorite and potentially chlorine, sodium hypochlorite, or hydrochloric acid)
- Requires advanced technical competence to operate and monitor equipment, product, and residuals
- Occasionally poses unique odor and taste problems from gas phase reactions
- Occupational inhalation toxicity risk
- Higher operating cost (sodium chlorite cost is high)
- Will not react with algal-or cyanobacteria-produced toxins

Non-Chlorine Alternative Disinfectants

Ozone   Ozone (O_3) gas is generated onsite at drinking water systems by passing dry oxygen or air through a system of high voltage electrodes. Ozone is one of the strongest oxidants and disinfectants available. Its high reactivity and low solubility, however, make it difficult to apply and control in drinking water treatment. Contact chambers are fully contained and non-absorbed ozone must be destroyed prior to release to avoid corrosive and inhalation toxicity conditions. Ozone is more often applied for oxidation purposes rather than disinfection alone.

ADVANTAGES

- Strongest oxidant/disinfectant available
- Does not directly produce chlorinated DBPs
- Effective against *Cryptosporidium*
- Used alone and in advanced oxidation processes to oxidize organic compounds
- Will react with algal- and cyanobacteria-produced toxins

LIMITATIONS

- Process operation and maintenance requires a higher level of technical competence
- Provides no residual disinfection
- Forms brominated DBPs by oxidation of bromide in the water
- Forms nonhalogenated DBPs (e.g., aldehydes)
- Degrades more complex organic matter; more biodegradable compounds can enhance microbial (re)growth in distribution systems and increase DBP formation during chemical disinfection
- Higher costs than chlorination due to capital costs, air or oxygen requirements, and electricity cost

- Difficult to control and monitor, particularly under variable load conditions

Ultraviolet Radiation   UV radiation, generated by mercury arc lamps, is a non-chemical disinfectant. When UV light penetrates the cell wall of an organism, it damages genetic material, and kills the cell or prevents reproduction. UV radiation has been shown to effectively inactivate many pathogens when sufficient doses of appropriate wavelengths are applied. Efficacy is dependent upon the delivered dose, transmissivity of the water, lamp spectral output, and intensity. Research on DBPs produced by UV radiation is ongoing.

ADVANTAGES

- Effective at inactivating most viruses, bacterial spores, and protozoan (oo)cysts at appropriate dosages
- No chemical generation, storage, or handling
- Effective against *Cryptosporidium* at low dosages
- Directly photolyzes nitrosamines and some other trace chemicals at appropriate doses and wavelengths

LIMITATIONS

- Provides no residual disinfection
- Higher doses of UV radiation are required to inactivate some viruses
- Difficult to monitor UV dosage and performance within a drinking water system
- Irradiated organisms can remain dormant and sometimes self-repair and reverse the destructive effects of UV radiation through a process called photo-reactivation
- Usually requires additional pretreatment steps to maintain

high-clarity water to maximize UV disinfection
- Does not provide oxidation or taste and odor control
- High cost of adding backup/emergency disinfection capacity
- Mercury lamps might pose a potable water and environmental toxicity risk; their output declines with time in use
- Will not react with algal- and cyanobacteria-produced toxins

7 The Future of Chlorine Disinfection

The preceding chapters discuss both disinfection opportunities and challenges facing drinking water providers. In response to increased regulations, emerging science on microbial contaminants and DBPs, as well as safety and security concerns related to treatment chemicals, water system managers and researchers will continue to evaluate chlorine and other disinfection methods in light of their unique circumstances. Despite challenges, many factors indicate that drinking water chlorination will remain a cornerstone of waterborne disease prevention and public health protection.

- Disinfection is unquestionably the most important step in drinking water treatment, and chlorine's wide range of efficacy and cost benefits cannot be provided by any other single disinfectant. Starting with its first continuous application in a U.S. municipality in 1908, drinking water chlorination continues to be hailed "as a giant step in public health protection" (McGuire, 2013).

- All disinfectants produce byproducts. Generally, the best approach to controlling DBPs is to remove natural organic matter precursors in raw water prior to disinfection (EPA, 2001b; WRF, 2017c).

- Chlorine has a relatively low taste threshold, so if taste-generating organic matter in source waters is minimized, a lower primary disinfection chlorine dosage is required and a lower free chlorine residual can be maintained. Combined chlorine residuals have a higher taste threshold than free chlorine residuals (IPCS, 2000).

- CDC's latest data for reported drinking water-associated disease outbreaks indicate that *Legionella* bacteria are the only waterborne pathogen that caused deaths in the United States from 2009 to 2014 (CDC, 2015, 2017a). *Legionella* are also the most common cause of these outbreaks, resulting in respiratory illness when people inhale water vapor or mists from contaminated showers, cooling towers, spas, and premise plumbing—all of which generally fall outside of federal and state regulatory oversight. Appropriate chlorine-based disinfection can help prevent future *Legionella* outbreaks. This can include short-term shock chlorination as well as maintaining an adequate chlorine residual throughout the distribution system.

- Only chlorine-based disinfectants can provide residual protection—an important part of the multi-barrier approach to protecting drinking water quality. Distribution system deficiencies due to aging infrastructure make residual disinfectants even more essential to protect public health.

- World leaders increasingly recognize safe drinking water as a critical building block of sustainable development (see **Box 7-1**). Chlorine that can be applied in several different forms can provide cost-effective, scalable disinfection for remote rural villages and large cities alike, helping to bring safe water to those in need.

Box 7-1: Safe Water—A Building Block for Sustainable Development

In 2000, the United Nations (UN) adopted a set of eight Millennium Development Goals (MDGs) to help improve the lives of the poorest people on Earth by 2015 (UN, 2015). Although the drinking water target under MDG #7 was met 5 years early, overall progress against the goals was mixed. The WHO (2018a,b) reported that in 2015:

- 71% of the global population (5.2 billion people) used a safely managed drinking water service; that is, one located on the premises, available when needed, and free from contamination

- 89% of the global population (6.5 billion people) used at least a basic service; that is, an improved drinking water source within a round trip of 30 minutes to collect water

- 844 million people lacked even a basic drinking water service

- 68% of the world's population (5.0 billion people) used at least a basic sanitation service

- 2.3 billion people still did not have basic sanitation facilities such as toilets or latrines

- At least 2 billion people used a drinking water source contaminated with feces

- Contaminated drinking water can transmit diseases such as diarrhea, cholera, and polio, and is estimated to cause over 502,000 diarrheal deaths each year, mostly in children in developing nations

As the MDG timeline drew to a close at the end of 2015, representatives of the global community developed a new set of 17 Sustainable Development Goals (SDGs) for the *Post-2015 SDG Agenda*. The new SDGs build on the MDGs, but are more specific, scientific, and measurable. Goal #6, "Ensure availability and sustainable management of water and sanitation for all," includes multiple targets and indicators such as improving water quality by reducing pollution and decreasing the proportion of untreated wastewater returned to the environment.

As a proven, scalable, and affordable disinfection technology available for household point-of-use, small community, and large municipal water systems alike, drinking water chlorination will help achieve SDG #6 in communities all over the world. Key to its unique usefulness is the long-lasting protective chlorine residual—an absolute necessity in areas of the world where intermittent, multi-purpose water supplies necessitate water storage and the distinct risk of microbial (re) contamination and disease outbreaks.

Glossary

Adsorption: Attachment of a substance to the surface of a solid.

Aquifer: A natural underground layer, often of sand or gravel that contains water.

Bacteria: Microorganisms composed of single cells whose DNA is not separated by an internal membrane. Bacteria may be classified in many different ways, such as based on their shape or how they respond to a violet dye in the Gram stain test (Gram-positive vs. Gram-negative bacteria).

Biofilm: An accumulation of microorganisms and organic and inorganic matter attached to the inner surfaces of water pipes and storage tanks. Biofilms are found in all distribution systems, regardless of water quality characteristics and pipe materials, and provide an environment for replication as well as protection against disinfectants.

Bioterrorism: Terrorism using biological agents.

Chlorination: The process of adding a form of chlorine to water for disinfection and/or oxidation.

Clarification: Removal of suspended solids from water by gravity sedimentation, aided by chemical flocculating agents.

Coagulation: Irreversible combination or aggregation of particles to form a larger mass that facilitates sedimentation (settling).

Coliforms: Bacteria that are present in the environment and in the feces of all warm-blooded animals and humans. Coliform counts provide a general indication of the sanitary condition of a water supply, but do not necessarily indicate fecal contamination.

Combined Chlorine: Chlorine that has reacted with ammonia or other reactive nitrogen compounds to form chloramines. Chloramines in water are in equilibrium with free chlorine. Combined chlorine is much less effective as a primary disinfectant than chlorine, but provides a longer-lasting level of residual protection.

Contact Time: C×T (mg/L × minutes) is the product of the residual concentration (C) of a disinfectant in mg/L and the contact time (T) in minutes at a particular temperature and pH. Contact time represents a consistent measure for comparing the efficacy of various disinfectants against a given microorganism.

Disinfection: Inactivation of harmful microorganisms by the use of chemical biocides or physical measures like heat or UV radiation.

Disinfection Byproducts (DBPs): Compounds created by the reaction of a disinfectant with organic compounds and some inorganic compounds in water.

Distribution System: A network of pipes leading from a treatment plant to customers' plumbing systems.

Emerging Pathogen: A pathogen that gains public health attention because it is either a newly recognized disease-causing organism, or an organism whose infectivity has increased.

Epidemiology: The study of the distribution and determinants of health-related states or events (including disease) and the application of this study to the control of diseases and other health problems.

Filtration: The operation of separating suspended solids from a liquid (or gas) by forcing the mixture through a porous barrier. The process operates by size exclusion and can be aided by charge interactions between the particles and the filter medium. Filters can be granular or membranes.

Flocculation: A process of adhesion and contact where dispersion particles form bigger clusters through mixing that settle more rapidly under gravity.

Free Chlorine: The sum of hypochlorous acid and hypochlorite ions, typically expressed as mg/L or ppm.

Groundwater: The water contained in aquifers (natural reservoirs below the earth's surface). Groundwater is a common source of drinking water. Groundwater is usually less likely than surface water to be affected by microbial contamination, but its chemical content reflects the local geology, and can be influenced by surface activities.

Haloacetic Acids: A group of DBPs that includes monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, bromoacetic acid, and dibromoacetic acid. This group is referred to as HAA5 and is currently regulated by EPA.

Hazard: The innate capacity of a substance to cause harm at some level of exposure.

Maximum Contaminant Level (MCL): The legal threshold limit of a contaminant that is permitted by EPA in drinking water. MCLs are set as close to maximum contaminant level goals (MCLGs) as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards and considered to be safe and protective of public health.

Maximum Contaminant Level Goal (MCLG): The level of a contaminant, determined by EPA and including an adequate margin of safety, at which there would be no known or anticipated risk to human health. This

goal is not always economically or technologically feasible, and the goal is not legally enforceable.

Microbial Contamination: Contamination of water supplies with microorganisms such as bacteria, viruses, and protozoa.

Microorganisms: Living, generally single-celled organisms that can be seen only with the aid of a microscope. Some microorganisms can cause health problems when consumed in or through drinking water; also known as microbes.

Nanofiltration: A pressure-driven membrane separation process that removes substances in the nanometer-range.

Nitrosamines: Compounds featuring a nitroso group bonded to an amine; class of nitrogenous-DBPs that can form when nitrogen-containing compounds react with certain oxidants/disinfectants.

Nitrification: The microbial process that converts ammonia and similar nitrogen compounds into nitrite (NO_2^-) and then nitrate (NO_3^-). Nitrification can occur in water systems treated with chloramine, and is greatest when temperatures are warm and water usage is low.

Organic Matter: Matter derived from organisms, such as plants and animals; typically measured in the aggregate as total organic carbon (TOC).

Oxidation: The process of an atom losing electrons and gaining positive valance.

Parasitic Protozoa: Single-celled microorganisms that utilize multicellular organisms, such as animals, as hosts.

Pathogen: A disease-causing microorganism.

pH: A measure of the acidity or alkalinity of an aqueous solution. The negative $\log_{10}$ of the hydrogen ion concentration between 0 and 14 in water. Acidic solutions have a pH below 7; basic solutions have a pH above 7.

Premise Plumbing: Plumbing inside houses, schools, health care facilities, and other buildings.

Raw (or Source) Water: Water in its natural state, prior to any treatment.

Residual: The persistent presence of chlorine or other disinfectant in water after treatment.

Reverse Osmosis: A pressure-driven membrane separation process that removes ions, salts, and nonvolatile organics.

Risk: The probability or likelihood that a substance can cause an adverse effect under some condition of exposure.

Surface Water: The water that is available from sources open to the atmosphere, such as rivers, lakes, and reservoirs. Surface sources provide the largest quantities of water for U.S. drinking water production. Surface water is more vulnerable to contamination than groundwater and generally requires more treatment.

Trihalomethanes (THMs): A group of regulated DBPs, each consisting of three halogen atoms (e.g., chlorine, bromine) and a hydrogen atom bonded to a single carbon atom. Includes chloroform, bromodichloromethane, bromoform, and dibromochloromethane.

Turbidity: The cloudy appearance of water caused by the presence of small particles that diffuse light. High levels of turbidity can interfere with proper chemical disinfection or UV efficacy.

Ultrafiltration: A pressure-driven membrane separation process that removes substances in the submicron (μ) particles and dissolved solutes.

Ultraviolet (UV) Radiation: Radiation in the region of the electromagnetic spectrum, including wavelengths from 100 to 400 nanometers.

Viruses: Microscopic infectious agents that can reproduce only within living host cells.

Waterborne Disease: Disease caused by an infective dose of microbial contaminants, such as bacteria, viruses, and protozoa in water. Chemicals in water can also cause illness.

Watershed (or Catchment): The land area from which water drains into a stream, river, or reservoir.

Zoonotic Disease: Disease that can spread from animals to humans; can be caused by viruses, bacteria, parasites, and fungi.

Acronyms and Abbreviations

ANSI	American National Standards Institute
AWWA	American Water Works Association
BDCM	Bromodichloromethane
CDC	U.S. Centers for Disease Control and Prevention
CFATS	Chemical Facility Anti-Terrorism Standards
DBA	Dibromoacetic acid
DBCM	Dibromochloromethane
DBP	Disinfection byproduct
DHS	U.S. Department of Homeland Security
EPA	U.S. Environmental Protection Agency
FWPCA	Federal Water Pollution Control Act
HAA	Haloacetic acid
HAA5	Group of five regulated haloacetic acids
IARC	International Agency for Research on Cancer
IPCS	International Programme on Chemical Safety (WHO)
LT1	Long Term 1 Enhanced Surface Water Treatment Rule
LT2	Long Term 2 Enhanced Surface Water Treatment Rule
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
MDG	Millennium Development Goals (UN)
NRC	National Research Council
NTU	Nephelometric Turbidity Unit
PAHO	Pan American Health Organization
PAM	Primary amoebic meningoencephalitis
ppb	Part(s) per billion (μg/L)
ppm	Part(s) per million (mg/L)
RTCR	Revised Total Coliform Rule
SAFETY	Support Anti-terrorism by Fostering Effective Technologies Act
SDG	Sustainable Development Goals (UN)
SDWA	Safe Drinking Water Act
THM	Trihalomethane
TTHM	Total trihalomethanes
TOC	Total organic carbon
UN	United Nations
U.S.	United States
UV	Ultraviolet
WBDOSS	Waterborne Disease and Outbreak Surveillance System (CDC)
WHO	World Health Organization
WRF	Water Research Foundation
WQHC	Water Quality & Health Council

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