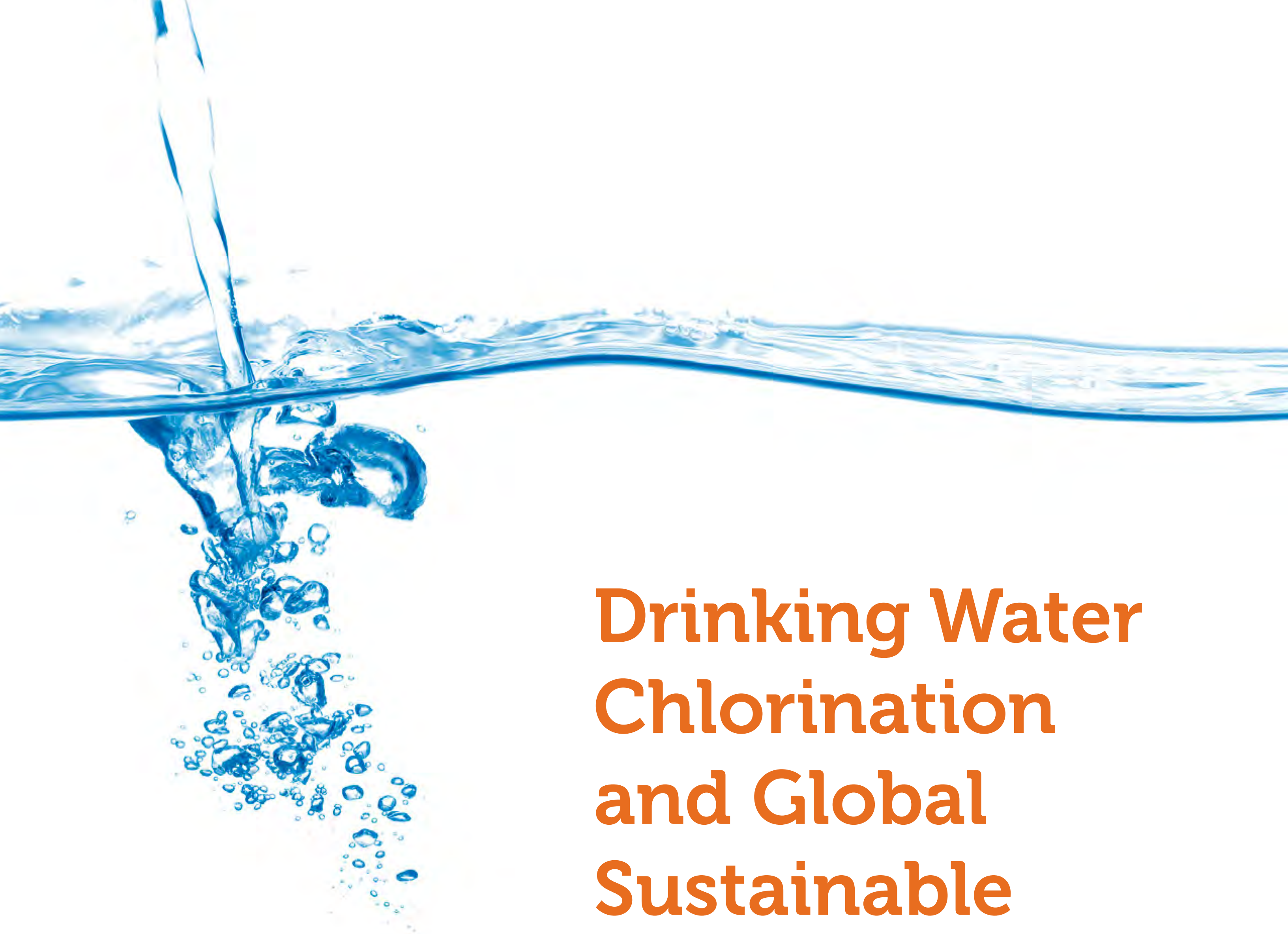


Drinking Water Chlorination and Global Sustainable Development

A Review of Disinfection Practices, Issues, and Public Health Benefits

American Chemistry Council

Contents

Foreword

In 2015, the United Nations (UN) announced 17 Sustainable Development Goals (SDGs), the centerpiece of the UN 2030 Agenda. These measurable, interconnected goals form a blueprint to achieve a better and more sustainable future for all by 2030. They challenge businesses, governments, and people in all countries to meet specific targets to promote prosperity, health, education, social justice, and environmental protection.

SDG #6, "Ensuring Access to Clean Water and Sanitation for All," and several of the other 16 SDGS, are directly linked to chlorine chemistry. Affordable and reliable chlorine-based disinfectants are a key factor in making safe drinking water and sanitation services available globally. Chlorine-based drinking water disinfectants are typically preferred because they are scalable from the smallest household point-of-use system, to community chlorinators, to regional state-of-the-art water treatment facilities. They also provide a unique residual level of disinfectant that continues working long after it is added to water. This helps keep water safe as it is stored in cisterns or flows to customers through piped distribution systems.

For more than a century, drinking water chlorination has drastically reduced waterborne disease. Developed nations have broadly implemented chlorine-based disinfection into drinking water treatment, which has virtually eliminated waterborne diseases in those countries. But millions of people around the world still do not have access to chlorine-based and other disinfectants to help make their drinking water safe. This leads to waterborne diseases that can cause death and widespread illness and suffering. The World Health Organization (WHO, 2018a) has estimated that drinking contaminated water can lead to over 500,000 diarrheal deaths each year, mostly in children in developing nations.

As the world strives to achieve the UN SDGs, drinking water chlorination will be central to achieving SDG #6, as well as several other critical SDGs. For example, access to safe, chlorinated drinking water will help achieve SDG #1, "No Poverty," by raising standards of health in poor, underserved communities, enabling residents to seek education and employment. Additionally, when safe drinking water is accessible to households everywhere, young girls will have increased opportunities to attend school regularly without being burdened with the task, as many are today, of obtaining water for their families from distant sources. This will be a major step forward in achieving SDG #5, "Gender Equality."

This booklet provides an overview of drinking water chlorination practices and issues, focusing in particular on the United States (U.S.). It includes discussions of the public health risks of exposure to waterborne pathogens, balancing the need for disinfection with managing disinfection byproducts, drinking water treatment security, and the future of chlorine disinfection. It is based on *Drinking Water Chlorination: A Review of U.S. Disinfection Practices and Issues*[1]. It is intended as a reference, not as a prescriptive guide for any particular chlorine-based drinking water disinfection application.

1 https://www.elementofsurprise.org/wp-content/uploads/2018/10/ACC_Overview_2018_WEB_r2b.pdf.

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 beginning in the early 1900s, diseases like 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.

Globally, most 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, drinking water 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 growth and regrowth 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 susceptible to waterborne disease.

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; that is, infections caused by pathogens that can spread from animals to humans.

Well-known bacterial pathogens, such as toxin-producing *Escherichia coli*, *Salmonella typhi*, and *Vibrio cholera*, as well as most 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, U.S. Environmental Protection Agency (USEPA) scientists and a Dutch researcher independently determined that drinking water chlorination could produce a group of DBPs known as trihalomethanes (THMs), including chloroform. USEPA 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 and increase DBP removal are available and should be adopted where possible. However, the 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. Protecting and controlling access to these critical infrastructure systems is an increasingly 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 tradeoffs 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 globally. Alternative disinfectants (including oxidants chlorine dioxide, ozone, and UV radiation) are available and, in some cases, appear to be gaining greater use in developed nations—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 and other decision-makers 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 UN, WHO, and other international organizations as a critical building block of sustainable development, particularly in the 2015 establishment of SDG #6, "Ensuring Access to Clean Water and Sanitation for All." 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. 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. 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 is chlorination.

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. Drinking water chlorination debuted in the United States in Jersey City, New Jersey, in September 1908, and resulted in a dramatic decline in the city's typhoid fever rates (McGuire, 2013).

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."

Providing Safe Drinking Water: A Multi-Barrier Approach

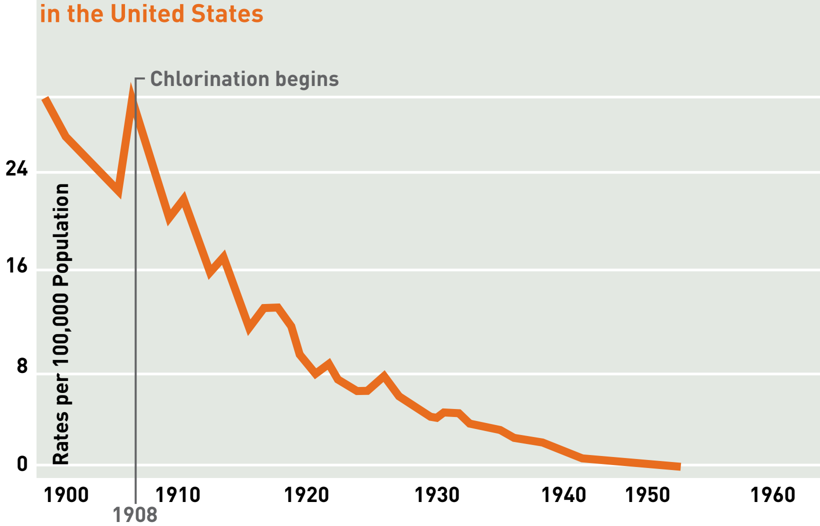
Meeting the goal of clean, safe drinking water requires a multi-barrier approach that includes protecting raw source water from contamination, appropriately treating raw water, and ensuring safe distribution of treated water to consumers' taps.

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.

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

In some areas of the world, communities are increasingly 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*. 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.

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



Source: CDC, 1997.

Water Treatment 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 often contains 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

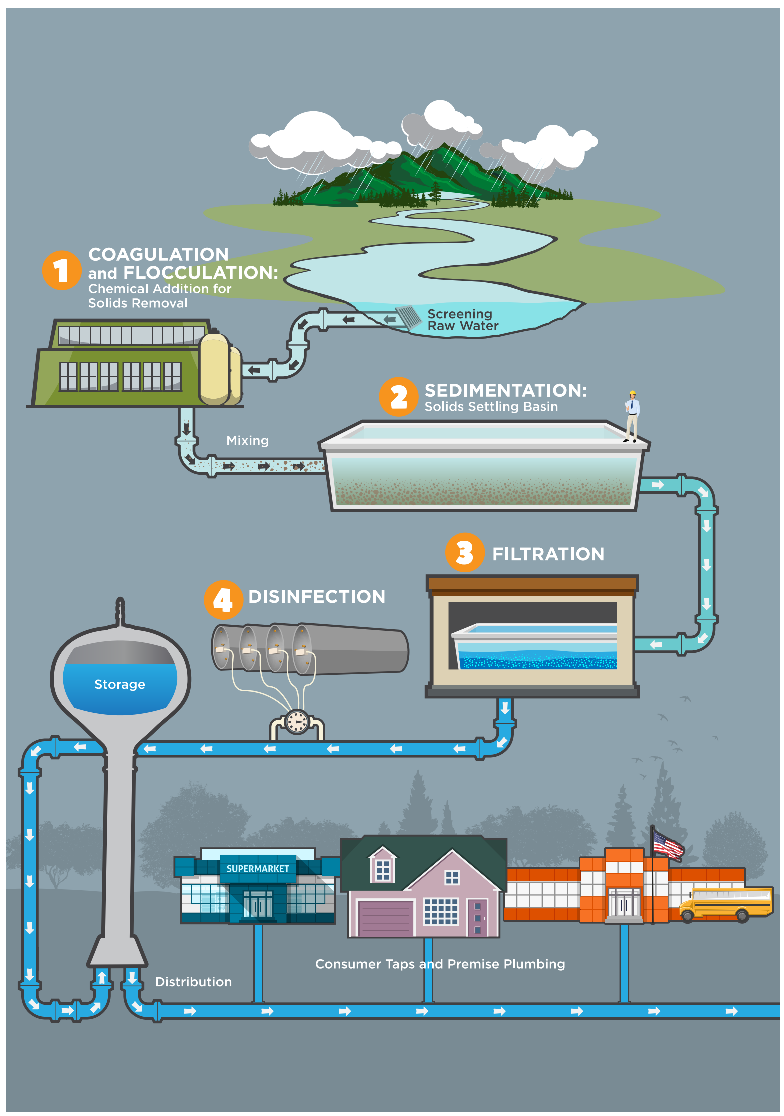
1. Coagulation and Flocculation remove dirt and other particles and some natural organics in the raw water. Alum (an aluminum sulfate) or other metal salts are added to raw water to form coagulated sticky masses called floc that attract other particles. Their combined weight causes the floc to sink during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

Globally, 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. When applied to water, each of these forms *free chlorine* (see **Box 2-1**). 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.

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

Many nations require or recommend a residual level of disinfection of water in pipelines to prevent microbial growth or regrowth and to help protect treated water throughout the distribution system. The USEPA's (1998) 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 (WHO, 2017), they can produce objectionable taste and odor concerns for some individuals.

Factors in Chlorine Disinfection: Concentration and Contact Time

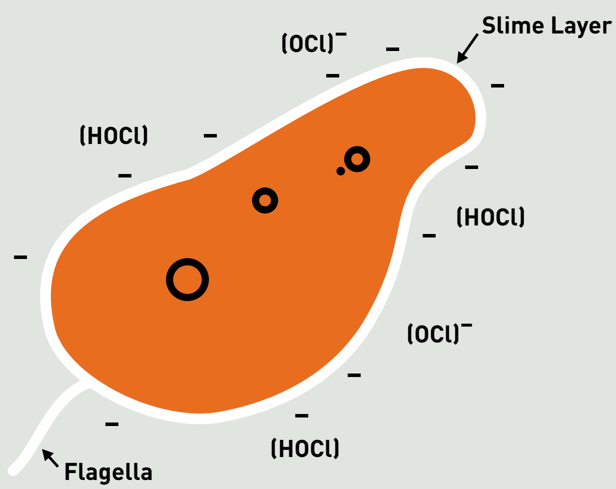
To establish more structured operating criteria for water treatment disinfection, the C×T concept came into use in 1980. C×T values—where C is final free chlorine concentration (mg/L) and T is minimum contact time in minutes—offer water treatment operators guidance in determining an effective combination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

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, hypochlorous acid dominates while at higher pH 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 UV 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.

3 The Risks of Waterborne Disease

Without adequate filtration and chlorination, contaminated drinking water presents an ongoing and 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). In the United States and other developed nations, these and other waterborne pathogens are now controlled routinely; however, 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, 2018b). Specific, measurable targets associated with UN SDG #6, "Ensuring Access to Clean Water and Sanitation," will help make safe drinking water available to all (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.

Vibrio cholerae (Dartmouth College/L. Howard)

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 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.

Bacteria

Bacteria are microorganisms composed of single cells shaped like rods, spheres, or spiral structures. Prior to widespread filtration and chlorination of U.S. 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. The Centers for Disease Control and Prevention (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.

E. coli (NIAID, NIH)

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 tract, 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

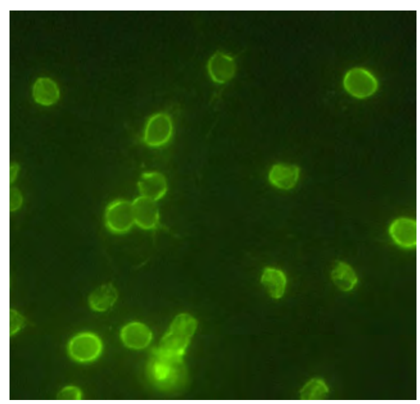
Protozoan parasites are single-celled microorganisms that feed on other microorganisms or multicellular organic tissues and debris. Several species of protozoan parasites are transmitted through water in dormant, environmentally-resistant forms, known as cysts and oocysts (Fletcher et al., 2012). The 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.

Legionella pneumophila (CDC/PHIL)

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 over 400,000 people in Milwaukee, Wisconsin, in 1993 with more than 100 deaths.

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, it is now well-recognized that all warm-blooded and some other animals can carry and transmit *Giardia*. 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).

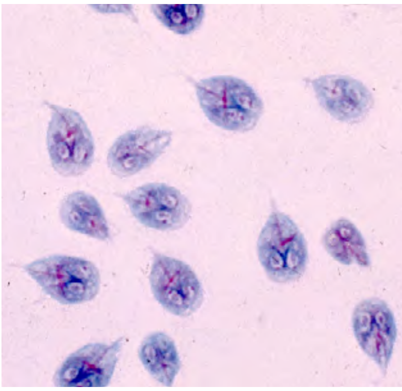
***Naegleria fowleri*—**Primary amoebic meningoencephalitis is a rare but deadly disease caused by waterborne *Naegleria fowleri*—a naturally-occurring, single-celled protozoan that thrives in soil as well as fresh, warm waters (lakes, rivers, ponds, and hot springs) (CDC, 2018). People enjoying these 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. Most infections occur in warmer climates during summer months when temperatures are higher and water levels low.



Cryptosporidium hominis (USEPA/H.D.A. Lindquist)

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; WHO, 2017). Although algae and cyanobacteria are not waterborne pathogens per se, one



Giardia intestinalis (CDC)

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 USEPA Rules to Control Waterborne Disease

Long Term 2 Enhanced Surface Water Treatment Rule—The USEPA 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 USEPA's LT2 Rule (USEPA, 2005) build on USEPA's Long Term 1 Enhanced Surface Water Treatment (LT1) Rule (USEPA, 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 (USEPA, 2005). Regardless of the primary disinfection method used, treatment plants must continue to maintain residual chlorine level disinfectants in their distribution systems.

Ground Water Rule—USEPA'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 and viruses (USEPA, 2006a).

Revised Total Coliform Rule—USEPA'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 (USEPA, 2013).

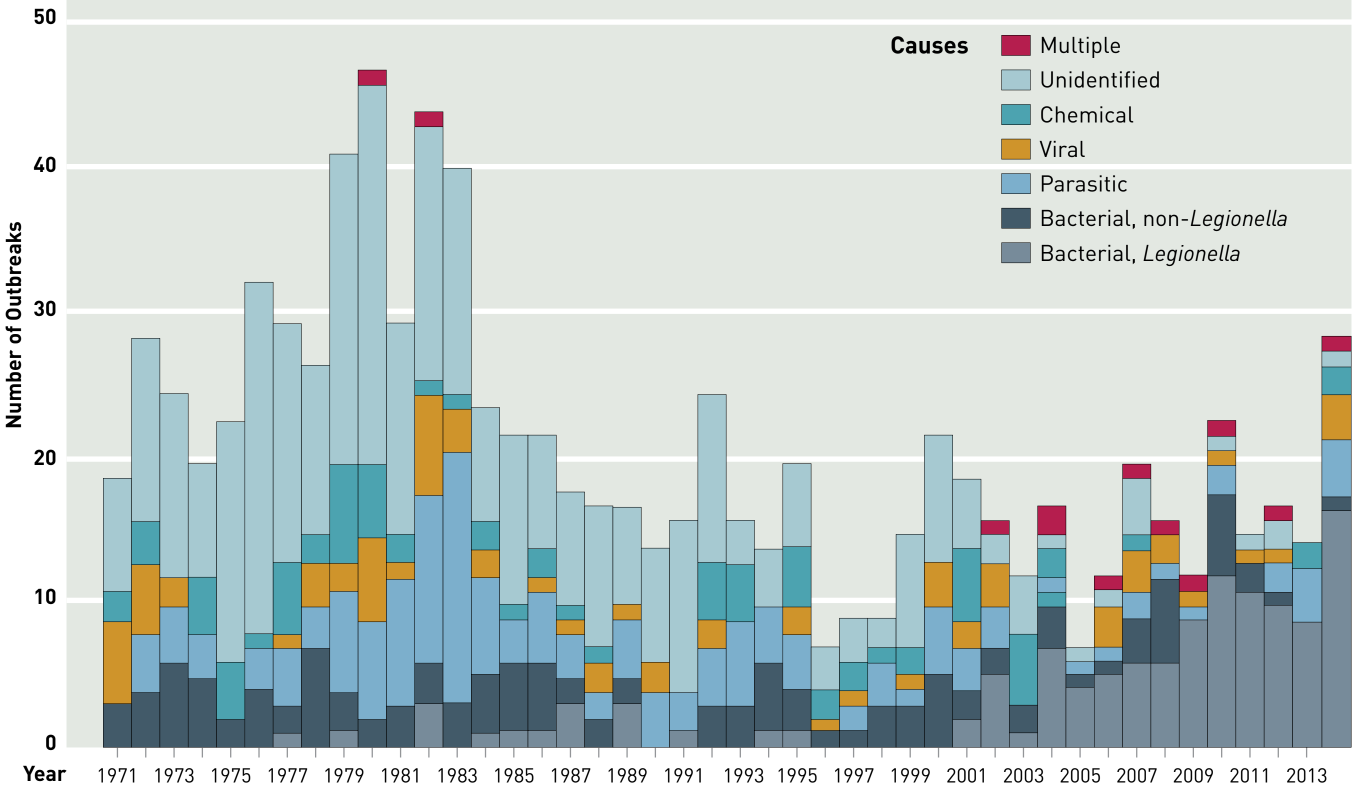
U.S. Waterborne Disease Trends

CDC and USEPA collaborate to track waterborne disease outbreaks of both microbial and chemical origin. In the United States, data on drinking water-related contamination have been collected and summarized since 1971 (2001 for *Legionella* bacteria), but it is important to emphasize that many waterborne disease outbreaks are neither detected nor reported.

The figures that follow are based on the most recent data (CDC, 2017a). **Figure 3-1** shows the number of drinking water-associated outbreaks in the United States 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. Not included in the preceding figure, but also an important finding from the CDC database, was that U.S. 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 U.S. outbreaks of waterborne disease 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 3-1: Causes of 928 Reported U.S. Drinking Water-Associated Outbreaks, by Year
Based on 1971–2014 CDC Data*



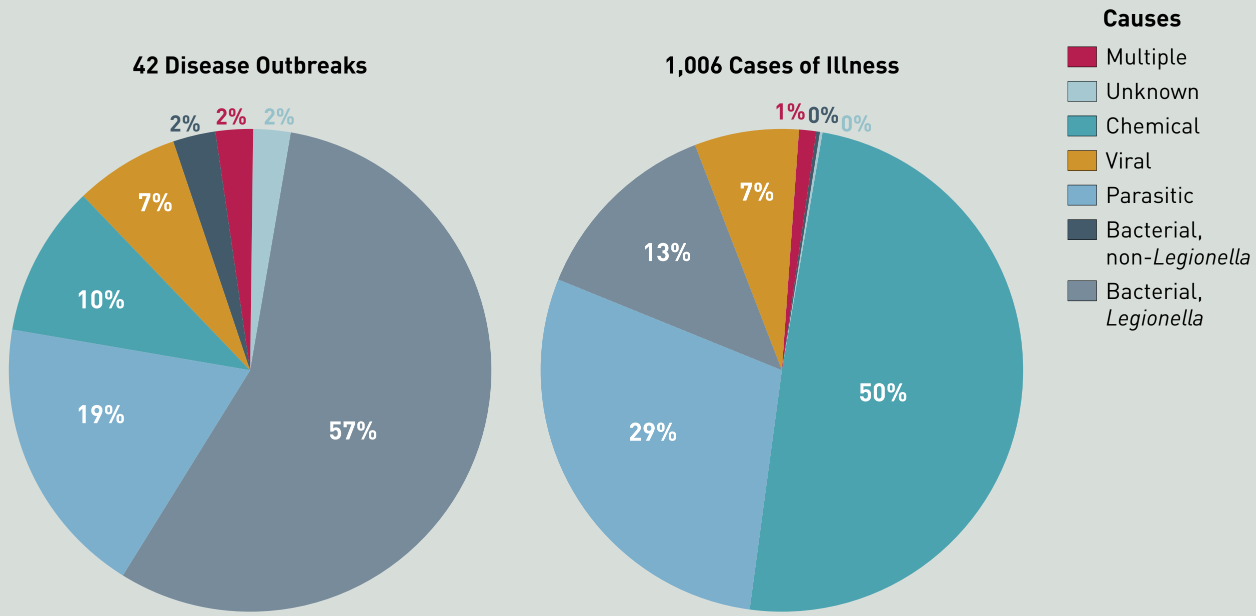
* Legionellosis outbreaks were first reported to CDC's Waterborne Disease and Outbreak Surveillance System in 2001; Legionellosis outbreaks before 2001 were added retrospectively during the 2007–2008 reporting period.

Source: Adapted from CDC, 2017a.

Collectively, the U.S. 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.

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



Source: Adapted from CDC, 2017a.

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

In recent years, researchers, 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 USEPA 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 bromoform concentrations is referred to as total trihalomethanes or TTHM. Based upon limited data, but concern that these chemicals might be carcinogenic to humans, USEPA 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 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 (USEPA, 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). TTHM and HAA5 standards can also be considered as drivers of treatment technologies that will also reduce many other DBPs.

The current USEPA 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 USEPA'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. USEPA 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 USEPA maximum contaminant level goals (MCLGs).

Epidemiology

TTHM regulations in the United 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 USEPA 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).

USEPA (2005, 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). An ecological study by Cotruvo and Amato (2019) that considered data from eight developed countries to probe trends in disinfection practices and bladder cancer incidence concluded that if there is a bladder cancer risk from drinking disinfected water, it "is small, and it is probably overwhelmed by many other larger factors such as smoking, diabetes, and other country-specific aspects."

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).

This finding is consistent with an 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 review in USEPA, 2016).

Updating the U.S. Safe Drinking Water Act Regulations

USEPA has regulated DBPs in drinking water since the late 1970s.

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

THM	IARC Designation	WHO Guideline (ppb)	USEPA 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: USEPA, 2018; WHO, 2017.

USEPA's Stage 1 Disinfectants and Disinfection Byproduct Rule

In 1998, the Stage 1 DBP Rule was established that lowered the TTHM MCL from 100 to 80 ppb (USEPA, 1998, 2001). 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. 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 treatment plants that use chlorine dioxide disinfectant), and bromate at 10 ppb (for plants that disinfect with ozone) (see USEPA, 2010).

In developing the Stage 1 DBP Rule in the late 1990s, USEPA 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.

USEPA's Stage 2 Disinfectants and Disinfection Byproduct Rule

A Stage 2 DBP Rule was promulgated in 2006, which supplements USEPA's 1998 Stage 1 DBP Rule (USEPA, 2006b). The Stage 2 DBP Rule is intended to reduce DBP exposures by limiting exposure to TTHM and HAA5. It still requires U.S. 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 changed how compliance was measured, recognizing that,"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 more stringent compliance requirements increase the probability of a TTHM and HAA5 MCL exceedance.

Balancing Disinfection Byproducts and Microbial Risks

The 1996 Safe Drinking Water Act (SDWA) Amendments required USEPA 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 waterborne 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 growth and regrowth, 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 U.S. 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 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:

1. Coagulation and Clarification
Many 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 iin 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 and decision-makers 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 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.

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, 2015.)

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 U.S. systems, security measures were primarily designed to protect facilities and equipment from pranks and vandalism. Today, protecting and controlling access to these critical systems is now a standard part of water system planning and operations.

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.

6 Comparing Disinfection Methods

Until the late 1970s, chlorine was virtually the only disinfectant used to treat drinking water in the United States and internationally. 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 growth and regrowth 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 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, standards, and guidelines
- Strengthening security at treatment facilities

To meet these challenges, water system managers and decision-makers 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, in some countries 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 growth and regrowth 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

- DBP formation (e.g., THMs, HAAs)
- 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 in North America, for example, 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 cyanobacteria-produced toxins

LIMITATIONS

- Hazardous pressurized gas requires special handling and operator training
- Additional regulatory and reporting requirements may apply

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 cyanobacteria-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 cyanobacteria-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 U.S. 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
- Does not form brominated DBPs
- 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 form brominated DBPs (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
- 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
- Forms nonhalogenated DBPs (e.g., aldehydes)
- Degrades more complex organic matter; more biodegradable compounds can enhance microbial growth and regrowth 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 cysts and oocysts 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.
- All disinfectants produce byproducts. Generally, the best approach to controlling DBPs is to remove natural organic matter precursors in raw water prior to disinfection (WHO, 2017; 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).
- *Legionella* bacteria are the most common cause of U.S. waterborne disease outbreaks (CDC, 2015, 2017a), resulting in respiratory illness when people inhale water vapor or mists from contaminated showers, cooling towers, spas, and premise plumbing. 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 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,c) 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, also known as the UN 2030 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 cost-effective 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. At the point of household use level in rural villages, several products are available for making raw water safe. For example, an inexpensive, powdered water treatment technology is available in a 4-gram packet. Each single-use packet includes enough chlorine-based disinfectant and other treatment chemicals to purify up to 10L of water to WHO guidelines. Moving up the scale of complexity, chlorinators for mid-sized communities in the developing world treat raw water in large stationary tanks through contact with a solid chlorine-based disinfectant. Community residents obtain safe water by filling storage containers at the chlorinator station and transporting them home. Significantly, both chlorine-based point-of-use products and community chlorinators utilize the very same disinfection chemistry to provide safe drinking water that conventional, piped municipal systems employ.

Key to its unique usefulness is the long-lasting protective chlorine residual—an absolute necessity in areas of the world where intermittent, multipurpose water supplies necessitate water storage and the distinct risk of microbial 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).

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: Killing or 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 USEPA.

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 USEPA 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 USEPA 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 log10 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

BDCM	Bromodichloromethane
CDC	U.S. Centers for Disease Control and Prevention
DBA	Dibromoacetic acid
DBCM	Dibromochloromethane
DBP	Disinfection byproduct
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 (USEPA)
LT2	Long Term 2 Enhanced Surface Water Treatment Rule (USEPA)
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
MDG	Millennium Development Goals (UN)
NRC	National Research Council
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
SDG	Sustainable Development Goals (UN)
SDWA	Safe Drinking Water Act (U.S.)
THM	Trihalomethane
TTHM	Total trihalomethanes
TOC	Total organic carbon
UN	United Nations
U.S.	United States
USEPA	U.S. Environmental Protection Agency
UV	Ultraviolet
WHO	World Health Organization
WRF	Water Research Foundation (U.S.)
WQHC	Water Quality & Health Council (U.S.)

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