

The term sick water was coined by the United Nations in a 2010 press release addressing the need to recognize that it is time to arrest the global tide of sick water. The gist of the United Nation's report was that transforming waste from a major health and environmental hazard into a clean, safe, and economically attractive resource is emerging as a key challenge in the 21st century. Practitioners of environmental health certainly support the United Nation's view on this important topic. When discussing sick water in the context of this text, however, it is necessary to go a few steps further than the United Nations did to describe the real essence and tragic implications of supposedly potable water that makes people or animals sick or worse. Water that is sick is actually filthy spent water or wastewater—a cocktail of fertilizer runoff and sewage disposal alongside animal, industrial, agricultural, and other wastes. In addition to these listed wastes of concern, other wastes are beginning to garner widespread attention. What are these other wastes? Any waste or product that we dispose of in our waters, that we flush down the toilet, pour down the sink or bathtub drain, or pour down the drain of a worksite deep sink. Consider the following example of pollutants we routinely discharge to our wastewater treatment plants or septic tanks—wastes we don't often consider as waste products but that in reality are. Each morning a family of four, two adults and two teenagers, wakes up and prepares for the day that lies ahead. Fortunately, this family has three upstairs bathrooms to accommodate everyone's needs, and each day the family's natural wastes, soap suds, cosmetics, hair treatments, vitamins, sunscreen, fragrances, and prescribed medications end up down the various drains. In addition, the overnight deposits of cat and dog waste are routinely picked up and flushed down the toilet. Let's examine a short inventory of what this family of four has disposed of or has applied to them- selves during their morning rituals:

• Toilet-flushed animal wastes • Prescription and over-the-counter therapeutic drugs • Veterinary drugs • Fragrances • Soap • Shampoo, conditioner, other hair treatment products • Body lotion, deodorant, body powder • Cosmetics • Sunscreen products • Diagnostic agents • Nutraceuticals (e.g., vitamins, medical foods, functional foods)

Even though these bioactive substances have been around for decades, today they are all (with the exception of animal wastes) grouped under the title of pharmaceuticals and personal care products, or PPCPs (see Figure 1). Returning to our family of four, after having applied, used, or ingested the various substances mentioned earlier, they also add at least traces of these products (PPCPs) to the environment through excretion (the elimination of waste material from the body) and bathing, as well as through disposal of any unwanted medications to sewers and trash. How many of us have found old prescriptions in the family medicine cabinet and disposed of them with a single toilet flush? Many of these medications (e.g., antibiotics) are not normally found in the environment. Earlier we stated that wastewater is a cocktail of fertilizer runoff and sewage disposal with additions of animal, industrial, agricultural, and other wastes. When we add PPCPs to this cocktail we can state that we are simply adding mix to the mix. This mixed-waste cocktail raises many questions: Does the disposal of antibiotics or other medications into the local wastewater treatment system cause problems for anyone or anything downstream? When we drink locally treated tap water are we also ingesting flushed-down-the-toilet or rinsed-down-the-drain antibiotics, other medications, illicit drugs, animal excretions, cosmetics, vitamins, personal or household cleaning products, sunscreen products, diagnostic agents, crankcase oil, grease, oil, fats, and veterinary drugs and hormones? If the family of four were shown the list of pharmaceuticals and personal care products they routinely used and disposed of each morning, they might be surprised, impressed, or totally un-

interested. Suppose, however, that after this family was shown the list of products they used and disposed of in the wastestream that left their home, they were asked if they would be willing to drink from that same wastestream. It is very likely that they would no longer be disinterested. In fact, they would probably be experiencing a queasy feeling in their stomachs that is commonly referred to as the “yuck factor.” The yuck factor raised by drinking human-created wastestreams is grossly overstated. The fact is we have been drinking from these wastestreams from time immemorial—beyond time or memory. Consider the mythical hero Hercules (arguably the world’s first environmental engineer), who performed his fifth labor by cleaning up King Augeas’ stables. Hercules, faced literally with a mountain of horse and cattle waste piled high in the stable area, had to devise some method to dispose of the waste. He diverted a couple of rivers to the stable interior, and they carried off all of the animal waste: Out of sight, out of mind. The waste followed the laws of gravity and flowed downstream, becoming someone else’s problem. Hercules understood the principal point in pollution control technology, one that is pertinent to this very day: Dilution is the solution to pollution. Apart from Hercules’ reasonable approach to disposing of waste in his time, another factor to consider is de facto water recycling. When the family of four and others say they would never drink toilet water, they have no idea what they are saying. As pointed out in the third edition of my textbook, *The Science of Water*, the fact is we drink recycled wastewater every day via the de facto water cycle, which turns the yuck factor into an “awe” factor. Wastewater treatment plants throughout the industrialized world treat wastewater or used water and then discharge the treated water to major rivers or other local water bodies. Many of those region’s rivers are sources of local drinking water supplies, and local groundwater supplies are routinely infiltrated with surface water inputs, which, again, are commonly supplied by treated wastewater (and sometimes infiltrated by raw sewage that is accidentally spilled). Nature takes care of the water pollution problem—to an extent; however, PPCPs may be the exception. The water cycle process results in some uncertainty regarding their fate, which is discussed in the text. The jury is still out on the topic of PPCPs. We simply do not know what we do not know about the fate of PPCPs or their impact on the environment once they enter our wastewater treatment systems, the water cycle, and eventually our drinking water supply systems. We do know that some PPCPs are easily broken down and processed by the human body or degraded quickly in the environment, but the disposal of certain wastes can be problematic for quite some time. Another issue related to contaminants in our water systems is one many of us never think about. Water is used by all living organisms, including wildlife and aquatic life. The fact is water pollution can severely harm marine, avian, and land animals. In addition to PPCPs, other contaminants found in our water bodies include the following:

- Raw sewage running into lakes, rivers or streams
- Industrial waste spills contaminating groundwater
- Radiation spills or nuclear accidents
- Illegal dumping of substances or items within bodies of water
- Biological contamination, such as bacterial growth
- Farm runoff into nearby bodies of water

It is also important to point out that drinking water sources and animal usage represent a double-edged sword. Animals have a right to drink from unpolluted and safe drinking water sources, but wildlife, farm animals, and other animals also contribute to drinking water pollution. This is why when in the woods or at campsites or other remote locates it is always wise to filter river, stream, or lake water with a 1-micron filter prior to drinking the water. The fly in this pollution solution ointment is today’s modern PPCPs. Although Hercules was able to dispose of animal waste into a running water system where eventually the water’s self-purification process cleaned the stream, he did not have to deal with today’s personal pharmaceuticals and

the hormones that are given to many types of livestock to enhance health and growth. Studies show that pharmaceuticals are present in our nation's water bodies, and research suggests that certain drugs may cause ecological harm. The USEPA and other research agencies are committed to investigating this topic and developing strategies to help protect the health of both the environment and the public. To date, scientists have found no hard evidence of adverse human health effects from PPCPs in the environment. Some might argue that these PPCPs represent only a small fraction (expressed in parts per trillion, 10–12) of the total volume of water, that we are speaking of a proportion equivalent to 1/20 of a drop of water diluted into an Olympic-size swimming pool. One student in an environmental health class stated that he did not think the water should be called “sick water,” as it was evident to him that water containing so many medications could not be sick. Instead, it might be termed “well water,” with the potential to make anyone who drinks it well. It is important to point out that the term sick water can be applied not only to PPCP-contaminated water but also to any filthy, dirty, contaminated, polluted, pathogen-filled drinking water sources. The fact is dirty or sick water means that, worldwide, more people now die from contaminated and polluted water than from all forms of violence, including wars.* The United Nations observed that dirty or sick water is a key factor in the rise of deoxygenated dead zones that have been emerging in seas and oceans across the globe. Preface to Third Edition The first and second editions of *The Drinking Water Handbook* were industrywide bestsellers hailed as masterly accounts written in an engaging, highly readable style. The third edition continues where the first two editions began—that is, stressing that notwithstanding our absolute need to breathe untainted air nothing is more important to us than the quality of the water we drink, although, of course, we need clean water for other uses as well. Written with the practitioner, student, novice, or sophisticated consumer in mind, this new edition of *The Drinking Water Handbook* has been thoroughly revised and updated and includes a comprehensive discussion of the Flint, Michigan, lead contamination event, pharmaceuticals and personal care products (PCPPs), and endocrine disruptors. With regard to our absolute need for air, water, and food, it is important to keep the 5–5–5 Rule in mind: Human beings can survive approximately 5 minutes without breathable air, 5 days without water, and 5 weeks without food. Keep in mind that this rule varies for each individual simply because we are all different and have different requirements. As a whole, however, the 5–5–5 Rule points to our absolute need for the three basic necessities needed to maintain life as we know it. All of the major cities of the modern world grew up on waterfronts but not because people require such large amounts of water for survival. People typically require no more than 10 pounds of water to create each pound of flesh, but to make a pound of paper requires approximately 250 pounds of water and to produce one pound of fertilizer requires 600 pounds. It is obvious that large cities developed near water primarily because of industry demands for a reliable water supply. In the United States, industry uses over 100 cubic miles of water every year to cool, wash, and circulate its materials, an amount equal to 30% of all the water in the rivers of the world. Of this water we use, very little goes back cleaner than when taken from its source, because as water travels it bears with it the story of where it has been and what it has been used for. This text recognizes the value of water for use in industry but is not about the industrial use of freshwater; instead, the focus here is on the use of freshwater by humans, who need pure, sweet, clean water to sustain them. This text is about the technology available and required to ensure that the water from our taps is safe. *The Drinking Water Handbook* focuses on keeping our drinking water supplies safe, on current problems with our drinking water supply, and on the technologies available to mitigate the problems. The dis-

cussion in this text relating to solutions and technologies is not the result of a “feel good” approach but rather is based on science and technology. Concern over water quality is not new. Throughout the history of human civilization, concern over the availability of clean drinking water has played an instrumental role in determining where people chose to settle and how these settlements grew into the cities of today. Those of us who reside in the United States are blessed with an abundant freshwater supply. Technology has even allowed us to provide for our arid areas; however, even with that abundance, economic development and population growth are straining the quality and quantity of water available for drinking. Trillions of gallons of precipitation fall on the United States every day, filling streams, rivers, ponds, lakes, and marshes. That water then percolates through the natural filter that is soil to recharge underground freshwater aquifers. Each day, agricultural irrigators, industrial users, factories, and homeowners withdraw hundreds of billions of gallons from this finite water supply. We use this water for everything from washing dishes and watering the garden to cooling the equipment of industrial complexes. After we are finished with it, the water (a substance always and forever in motion) finds a path back into the water cycle—into a stream, river, pond, lake, marsh, or groundwater supply—along with whatever contaminants it picked up along the way. When we open our taps to fill our glasses with drinking water, we expect good quality of the water as a basic right. As far as most of us are concerned, what comes from the tap is safe and will cause us no harm. Is this really the case, though? Is the water from our taps really safe? We are hearing now that cancer-causing chemicals exist in virtually every public water supply in the United States. As water pours forth from the tap into our drinking glasses, another point of concern arises. Has the water been tested in accordance with applicable standards or requirements? Were the tests reliable, or not? Most public health officials claim that our drinking water is safe, but do they really know that for sure? Are federal and state standards for water safety adequate? This revised and updated edition of *The Drinking Water Handbook* provides technical information regarding what can be found in many tap-water supplies and the measures taken to ensure the health and well-being of consumers. The *Drinking Water Handbook* starts at the source itself, and describes the water purification process through distribution to the tap, to our actual use and reuse of water. Water, a substance we constantly use and reuse, is recycled via the hydrologic (water) cycle. This text focuses on a particular water cycle, the artificial water cycle that we have created, control, and are utterly dependent on. Called the urban water cycle, it consists of the water supply, water purification, water use, and water disposal for reuse common in major metropolitan areas—a manmade cycle that mimics the natural water cycle. As water users directly affected by the quality of our water, we must take the necessary steps to protect our health by making sure that the water available for drinking is safe—a task not easy to accomplish. We cannot tell the quality of our water just by looking at it; we know that water can look clear in the glass and still contain toxic chemicals or bacterial and viral pathogens that can make users sick. To purify water, communities rely on municipal treatment plants and a variety of technologies ranging from simple screens, sand filtration, and disinfection to complex chemical and mechanical processes. These systems are not fail safe, though. When they do fail (more often than you might think), water users are left vulnerable to a wide variety of biological and chemical hazards, whether they know it or not. In 1993, a microscopic organism called *Cryptosporidium* caused more than 400,000 illnesses in Milwaukee, Wisconsin, and left 100 people dead. In 1994, two more outbreaks of the same protozoa killed 19 and sickened more than 100 in Las Vegas, Nevada. Panic over *Cryptosporidium* and *Giardia* caused a 2-month-long boil-alert crisis in Sydney, Australia, between

July and September of 1998, one that ended up costing millions of dollars, although no illnesses resulted. That treatment facility paid enormous penalties for incompetent testing—and for not following the maxim, “Better safe than sorry.” Many water users and technologists are no longer ignorant of the current drinking water crisis; the publicity generated by the events in Milwaukee, Las Vegas, and Sydney took care of that. The reappearance of *Cryptosporidium* had an immediate effect. Microbiological parameters and controls returned to the forefront, after having been demoted in the 1970s; disinfection, along with more sophisticated water treatment, came back into favor. Overnight, *Cryptosporidium* and *Giardia* became urgent targets of concern, and the fear of carcinogens (e.g., radon, lead, arsenic) was no longer at the top of the regulatory agenda. In late 1998, concerns about *Cryptosporidium* and *Giardia* were joined by not necessarily a new concern but a concern with new emphasis: disinfection byproducts, including halogenated chloroorganic compounds such as trihalomethanes (THMs). A partial result of these concerns has been the emergence of a new bottled-water industry, one growing at tremendous speed. Consumers want assurance that their water is safe, no matter what, and the current perception is that bottled water is safer than tap water. Another problem, although not a new one, is pharmaceuticals and personal care products (PPCPs) as pollutants. These pollutants are derived from products used by individuals for personal health or cosmetic reasons or used by agribusiness to enhance the growth or health of livestock. Comprising a diverse collection of thousands of chemicals substances, PPCPs include prescription and over-the-counter therapeutic drugs, veterinary drugs, fragrances, and cosmetics. PPCPs have been present in water and the environment for as long as humans have been using them. The problem with PPCPs in our water supplies is that we do not know what we do not know about their possible impact on human health and the environment. Recent advances in technology, however, have improved our ability to detect and quantify these chemicals, so we can now begin to identify what effects, if any, these chemicals have on human and environmental health. We discuss each of these pressing concerns in this edition of the text. In the not too distant past, determining whether a surface water source for drinking water was contaminated was accomplished by placing a healthy fish into a stream. If the fish died, the source was contaminated and therefore had to be purified. The degree of contamination was calculated by dividing 100 by the survival time in minutes. Our testing is by far more complex today, but sometimes not much more reliable. Although primarily designed as an information source and presented in simple, straightforward, easy-to-understand plain English, *The Drinking Water Handbook* also provides a level-headed account, based on years of extensive research, of drinking water quality. *The Drinking Water Handbook* is suitable for use by both the technical practitioner in the field and by students in the classroom. Here is all the information you need to make technical or personal decisions about drinking water.

Introduction SETTING THE STAGE Our goal in this book is to take a prosaic subject and make it endlessly fascinating . . . and totally appreciated. Many might question how anyone could make the topic of water fascinating, but consider that water is a contradiction, a riddle. A case in point is an old Chinese proverb: “Water can both float and sink a boat.” Water’s presence everywhere feeds these contradictions. Lewis (1996) pointed out that, “Water is the key ingredient of mother’s milk and snake venom, honey and tears.” Leonardo da Vinci gave us insight into more of these apparent contradictions:

Water is sometimes sharp and sometimes strong, sometimes acid and sometimes bitter. Water is sometimes sweet and sometimes thick or thin. Water sometimes is seen bringing hurt or pestilence, sometimes health-giving, sometimes poisonous. Water suffers changes into as many natures as are the different places through which it passes. Water, as with the mirror that changes with the color of its object, so it alters with the nature of the place, becoming: noisome, laxative, astringent, sulfurous, salt, incarnadined, mournful, raging, angry, red, yellow, green, black, blue, greasy, fat or slim. Water sometimes starts a conflagration, sometimes it extinguishes one. Water is warm and is cold. Water carries away or sets down. Water hollows out or builds up. Water tears down or establishes. Water empties or fills. Water raises itself or burrows down. Water spreads or is still. Water is the cause at times of life or death, or increase of privation, nourishes at times and at others does the contrary. Water, at times has a tang, at times it is without savor. Water sometimes submerges the valleys with great flood. In time and with water, everything changes.

We can sum up water's contradictions by stating that, although the globe is awash in it, water is no single thing but an elemental force that shapes our existence. Leonardo's last observation, "In time and with water, everything changes," concerns us most in this text. Why? We stated in the Preface that, next to the air we breathe, the water we drink is most important to us—to all of us. Water is no less important than air, simply less urgent. For all of us, although we treat it casually, unthinkingly, water is not a novelty but a necessity. We simply cannot live without water. Some might view such statements about the vital importance of water (commonly and incorrectly considered a rather plain and simple substance) as nothing more than hyperbole, exaggeration, panic, or overstatement. But are they? Is the concern for safe drinking water really an exaggeration? No, it is not, because we were all born of water and to live we must be sustained by it. The development of safe drinking water supplies is a major concern today, which might seem strange to those who might literally be surrounded by various bodies of water. Drinking water practitioners—those responsible for finding a source of drinking water, certifying its safety, and providing it to the consumer—know that two key concerns drive the development of safe drinking water supplies: quantity and quality. Herein lies the problem. Quantity may indeed be a major issue (a limiting factor) for a particular location, often simply because water suitable for consumption is not evenly distributed throughout the world. Those locations fortunate to have an ample supply of surface water or groundwater may not have a quantity problem, as long as the quantity is large enough to fulfill the needs of all its consumers. But, again, not every geographical location is fortunate enough to have an adequate water supply—that is, a quantity of water available to satisfy the residents' needs. Of course, this is one of the primary reasons why major portions of the globe are either uninhabited or sparsely populated at best. Not all the news on the topic of water is bad. Extreme water quantity issues do not necessarily suggest that a location will fall victim to scarcity. Water quantity issues can be managed. Given the right information and a high degree of common sense, locations facing extremely significant quantity issues can implement management and conservation strategies to secure their water supplies. Take Singapore, for example. The area is highly populated with a booming economic capacity, even though the location lacks adequate surface or groundwater sources of water. Singapore's demand for water far exceeds its naturally occurring supply, so if one wants to look at an example of effective water management, then Singapore is the place. To meet its freshwater needs, Singapore invests heavily in technology, responsible management, and international agreements. For example, forward-thinking and innovative management practices, in-

cluding the use of advanced rainwater capture systems, account for at least 20% of Singapore's water supply, where the total annual precipitation averages 2150 mm (84.6 in.), equivalent to 2150 L/m² or 52.73 gal/ft². Another 40% of Singapore's water supply is imported from Malaysia. The use of gray water or sullage (i.e., wastewater generated in homes and offices that is non-toilet water) adds 30% to the total, with desalinization producing the remaining 10% of the supply necessary to meet the location's total demand. Unfortunately, Singapore is the exception today, not the trend. For this reason, among other contributing factors, major portions of the globe remain either uninhabited or sparsely populated. The other key concern (and the main focus of this text) is water quality. Obviously, having a sufficient quantity of freshwater available does little good if the water is unsafe for consumption or for other uses. There is another issue; namely, it is rather easy to determine the quantity of a substance such as water. We can say there is too little, enough, or too much. A quantity is a metric that indicates or signifies a number. In the case of water, quantity can be expressed as the number of gallons or acre-feet of water available or not available. Trying to quantify the quality of water is an entirely different matter, though. Quality is a characteristic that often is a judgment call, but the problem with judging quality is that it can be subjective. To make our point about quality being a judgment call, consider Figure 1.1. The figure shows three glasses, labeled A, B, and C. Each glass contains icewater. The glasses were filled from three different household taps and three different household ice-cube trays from three different locations. If you had a choice of which of the three glasses of icewater to drink, which would you choose? Discerning individuals, people who are concerned about the appearance of their water, would probably make a judgment call and choose glass A because it looks like it contains cleaner water. Others might select either glass A or glass B, because there appears to be such a slight difference between the appearances of each that it is not a big deal. Again, a judgment call. On the other hand, glass C would probably only be chosen by someone so thirsty, so desperate, or so blind as to not care which glass they are drinking from—a nonjudgmental call, for sure. Sometimes, there might not be a real choice. Maybe only the water shown in glass C is available. Is that not what happened in Flint, Michigan? Figure 1.1 makes our point about quality and personal judgment calls. Again, although quantity can usually be expressed using simple metrics (a gallon or ounce or teaspoon of this or that, etc.), quality is a completely different issue. The appearance of anything we intend to put into our mouths is certainly a quality factor, but keep in mind that quality judgments can be based on other factors, as well. In the case of drinking water, we expect that our glass of tap water will contain water that is odorless, tasteless, and transparent. We also expect our glass of tap water to be safe. We expect it to be pure and free from biological or chemical contamination. This point brings us to another important aspect concerning the three glasses of water shown in Figure 1.1. It was suggested that the discerning person would most likely choose glass A simply because it looks like it contains the cleanest water of the three glasses. But is it really the safest water? How would one know for sure that glass A does not contain deadly bacteria? How would one know for sure that the same glass of water does not contain invisible and harmful chemicals? In addition, a person who is both discerning and knowing might question why none of the ice is floating in any of the three glasses. Why aren't the ice cubes floating? Is there something in the water used to make the ice cubes that is preventing them from floating? Because the ice cubes are not floating, water scientists would avoid all three glasses. Later discussion addresses water contaminants and how they are prevented from entering or are removed from our tap water supplies. The bottom line: Obviously, having a sufficient quantity of freshwater available does

little good if the water is unsafe for consumption or for other uses. Let's return to our stage setting for the contents of this book. We began this chapter by revealing some of the contradictions water presents, but there is another one—one that human beings bear considerable responsibility for. Consider that most of the early settlements of the world began along waterways. Waterways were important primarily because of the ease of transportation they afforded and because of their industrial value (e.g., water power), in addition to serving as a source of food for the settlers. And, of course, such waterways provided a natural, relatively clean, relatively safe source of drinking water. Unfortunately, these early waterways soon became polluted. This should not be surprising, though, as humans have always been polluters. We can actually say that pollution is a natural byproduct of civilization. We eat, we work, we do whatever is necessary to sustain our existence, and in doing so we pollute. Are we the only freshwater polluter? Not really. Natural events also pollute our water sources, especially our surface waters; for example, a stream that flows through a heavily wooded area (such as a deciduous forest) suffers from the effects of natural pollution each year during leaf-fall. When leaves fall from their lofty perches and make their sinuous descent into the blue-green phantoms we call surface streams below, they are carried with the flow, drifting until they sink, are saturated, or become lodged in an obstruction in the stream. Leaves are organic and eventually degrade. During this process, the microbes degrading the leaves take up and use dissolved oxygen in the water. In some cases, the amount of oxygen used during degradation is of such quantity, especially in slow-moving or stagnant areas of water, that the natural biota in the stream suffer from a lack of oxygen. When this happens, they either move on to healthier parts of the stream or succumb because of a lack of oxygen. Note that other natural water polluters also affect water quality, including forest fires, earthquakes, and floods. Remember that Nature understands the contradictions of water . . . and because she understands, she is also well suited and equipped to deal with such problems. When a stream becomes polluted (for whatever reason), Nature immediately goes to work to set in motion natural processes—known as self-purification—designed to restore the stream to its normal, healthy state. Only when such streams become overloaded with pollution or with nonbiodegradable manmade contaminants does Nature have difficulty in restoring the stream to its normal quality. Legend also has it that Alexander the Great discovered Adam's will, which indicated that God had created a spring beyond the mountains surrounding the world, in the Land of Darkness. This spring was unique—"whiter than milk, colder than ice, sweeter than honey, softer than butter, and sweeter smelling than musk" (Varner, 2006). Those who drank from it would be granted eternal life. Will this book lead you to that spring and eternal life? Probably not. Instead, this text is intended to serve as a convenient, quick reference and to provide technical support in the hands of the general public, sanitary engineers, public health administrators, public works engineers, water treatment operators, and college students in environmental health or public health engineering. The purpose of this handbook is to evaluate and emphasize drinking water quality control, from the source to the treatment plant, from the distribution system to the consumer. The goal is to look closely at the factors that affect water quality, including trihalomethanes, *Cryptosporidium*, viruses, carcinogens, and polychlorinated biphenyls, in addition to the traditional physical, chemical, and bacteriological parameters. This handbook addresses the challenges faced by drinking water practitioners striving to provide the best drinking water quality to the consumer. Specifically, it deals with the nature of these challenges (unsafe drinking water) and their solutions (how to make it safe), in addition to exploring techniques that can be employed to mitigate the problem of un-

safe drinking water through technology. The focus is on science and technology rather than “feel good” approaches simply because of a clear understanding that technology and politics are seldom a rational mix. All About Water: Basic Concepts EARTH’S BLOOD The watery environment in which single-cell organisms live provides them food and removes their wastes, a function that the human circulatory system similarly provides for the 60 to 100 trillion cells in a human body. The circulatory system brings each cell its daily supply of nutritive amino acids and glucose and carries away waste carbon dioxide and ammonia, which will be filtered out of our systems and flushed away through micturition and excretory functions. The heart, the center of our circulatory system, keeps blood moving on its predetermined circular path, a function so essential that if the pump fails we quickly fail as well—and we die. As single-celled organisms no longer, humans sometimes assume that they no longer need a watery environment in which to live—but they aren’t paying close attention to the world around them. Actually, those of us who live on Earth are as dependent upon the Earth’s circulatory system as we are on our own circulatory system. Just as the human heart pumps blood, circulating it through a series of vessels, and just as our lives are dependent upon that flow of blood, so life on Earth is dependent on the Earth’s water cycle.

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This cycle is so automatic that we generally ignore it until we are slapped in the face by it. Just as we do not pay attention to the beating of our heart unless it skips a beat or falters, until we are confronted by flood or drought or until our plans are disrupted by rain, we ignore the water cycle, preferring to believe that the water we drink comes out of the faucet, not from deep within the belly of the Earth, placed there by a process we only dimly comprehend. But, water is as essential to us and to the Earth as blood is in our bodies, and the constant cycle that water travels through makes our lives possible. Earth’s blood, water, is pumped, not by a heart, but by the hydrologic cycle—the water cycle. A titanic force of nature, the water cycle is beyond our control—a fact that we ignore until weather patterns shift and inundated rivers suddenly flow where they will and not within human-engineered banks, floodwalls, dikes, or levees. In the water cycle, water evaporates from the oceans; falls as rain, hail, sleet, or snow; and strikes the Earth again . . . thus, the cycle continues. In cities, in summer, rain strikes hot cement and asphalt and evaporates or runs into storm drains, swiftly rejoining the cycle. In fields, rain brings essential moisture to crops and, sinking deeper into the Earth, ends up as groundwater. If water strikes a forested area, the forest canopy breaks the force of the falling drops. The forest floor, carpeted in twigs, leaves, moss, and dead and decaying vegetation, keeps the soil from splashing away as the water returns to the depths of the Earth or runs over the land to join a stream. Whenever water strikes the Earth, it flows along four pathways that carry water through the cycle just as our veins, arteries, and capillaries carry our blood to our cells. Water may evaporate directly back into the air. It may flow overland into a stream as runoff. It may soak into the ground and be taken up by plants for evapotranspiration. Or, water may seep down to become groundwater. Whatever pathway it takes, one fact is certain: Water is dynamic, vital, constantly on the move. And, like human blood, which sustains our lives, Earth’s blood, to sustain us as well, must continue to flow (Spellman, 2007).

INTRODUCTION Take a moment to perform an action most people never think about doing. Hold a glass of water (like the one shown in Figure 2.1) and think about the substance within the glass—about the substance you are getting ready to drink. Also, think about the ice cubes floating in the glass, unlike those shown in Figure 1.1. The drinking glass full of water and ice cubes—the water we are about

to drink, the water we do drink—is not one of those items people usually spend much thought on, unless they are tasked with providing that drinking water or are dying of thirst.

Let's think about that water now, though. Water is special, strange, and different. Water can be a fascinating subject worthy of considerable interest because of its unique behavior, endless utility, and ultimate and intimate connection with our existence. The author agrees with Robbins (1976), whose description of water follows:

Stylishly composed in any situation—solid, gas, or liquid—speaking in penetrating dialects understood by all things—animal, vegetable or mineral—water travels intrepidly through four dimensions, sustaining (Kick a lettuce in the field and it will yell “Water!”) destroying (The Dutch boy's finger remembered the view from Ararat) and creating (It has even been said that human beings were invented by water as a device for transporting itself from one place to another, but that's another story). Always in motion, ever-flowing (whether at stream rate or glacier speed), rhythmic, dynamic, ubiquitous, changing and working its changes, a mathematics turned wrong side out, a philosophy in reverse, the ongoing odyssey of water is irresistible.

Let's review a few basic facts about that glass of water: Water is liquid between 0°C and 100°C (32°F and 212°F), solid at or below 0°C (32°F), and gaseous at or above 100°C (212°F). One gallon of water weighs 8.33 pounds (3.778 kilograms), and one gallon of water equals 3.785 liters. One cubic foot of water equals 7.50 gallons (28.35 liters). One ton of water equals 240 gallons. One acre-foot of water equals 43,560 cubic feet (325,900 gallons). Earth's rate of rainfall equals 340 cubic miles per day (16 million tons per second). As Robbins observed, water is always in motion. The one most essential characteristic of water is that it is dynamic: Water constantly evaporates from seas, lakes, and soil and transpires from foliage. It is transported through the atmosphere and falls to Earth, where it runs across the land and filters down to flow along rock strata into aquifers. Eventually, water finds its way to the sea again—indeed, water never stops moving. A thought that might not have occurred to most people looking at a glass of water is, “Has someone tasted this same water before us?” Absolutely. Remember, water is essentially a finite entity. What we have now is what we have had in the past. We

are drinking the same water consumed by Cleopatra, Aristotle, Leonardo da Vinci, Napoleon, Joan of Arc (and several billion other folks who preceded us)—because water is dynamic (never at rest) and because water constantly cycles and recycles, as discussed in the next section.

THE WATER CYCLE The natural water cycle or hydrologic cycle (the journey water takes during its constant, inevitable motion) is the means by which water in all three forms—solid, liquid, and vapor—circulates through the biosphere. Water lost from the Earth's surface to the atmosphere, either by evaporation from the surface of lakes, rivers, and oceans or through the transpiration of plants, forms clouds that condense to deposit moisture on the land and sea. A drop of water may travel thousands of miles between the time it evaporates and the time it falls to Earth again as rain, sleet, or snow. The water that collects on land flows to the ocean in streams and rivers or seeps into the Earth, joining groundwater.

Even groundwater eventually flows toward the ocean for recycling (see Figure 2.2). Note: Only about 2% of the water absorbed into plant roots is used in photosynthesis. Nearly all of it travels through the plant to the leaves, where transpiration to the atmosphere begins the cycle again. Note: The hydrologic cycle describes water's circulation through the environment. Evaporation, transpiration, runoff, and precipitation describe specific water movements. When humans intervene in the natural water cycle, they generate

artificial water cycles or urban water cycles (local subsystems of the water cycle—an integrated water cycle) (see Figure 2.3). Although many communities withdraw groundwater for public supply, the majority rely on surface sources. After treatment, water is distributed to households and industries. Water that is wasted (wastewater) is collected in a sewer system and transported to a treatment plant for processing prior to disposal. Current processing technologies provide only partial recovery of the original water quality. The upstream community (the first water user, shown in Figure 2.3) is able to achieve additional quality improvement by dilution into a surface water body and natural purification; however, as shown in the figure, the next community downstream is likely to withdraw the water for a drinking water supply before complete restoration. This practice is intensified and further complicated as existing communities continue to grow and new communities spring up along the same watercourse. Obviously, increases in the number of users bring an additional need for increased quantities of water. This withdrawal and return process by successive communities in a river basin results in indirect water reuse (use of used toilet water via water recycling).

The indirect water reuse process (demonstrated in Figure 2.3) is a clear example of combining an artificial water cycle with the natural hydrologic scheme and involves (1) surface water withdrawal, processing, and distribution; (2) wastewater collection, treatment, and disposal back to surface water by dilution; (3) natural purification in a river; and (4) repetition of this scheme by communities downstream (Hammer and Hammer, 1996). **WATER SUPPLY: THE Q AND Q FACTORS** Whereas drinking water practitioners must have a clear and complete understanding of the natural and manmade water cycles, they must also factor in the two major considerations of quantity and quality, the Q and Q factors. They are responsible for (1) providing a quality potable water supply—one that is clean, wholesome, and safe to drink; and (2) finding a water supply in adequate quantities to meet the anticipated demand. Note: Two central facts important to our discussion of freshwater supplies are that (1) water is very much a local or regional resource, and (2) problems of its shortage or pollution are equally local problems. Human activities affect the quantity of water available at a locale at any time by changing either the total volume that exists there or aspects of quality that restrict or devalue it for a particular use.

Thus, the total human impact on water supplies is the sum of the separate human impacts on the various drainage basins and groundwater aquifers. In the global system, the central, critical fact about water is the natural variation in its availability (Meyer, 1996). Simply put, not all lands are watered equally. To meet the Q and Q requirements of a potential water supply, the drinking water practitioner (whether it be the design engineer, community planner, plant manager, plant administrator, plant engineer, or other responsible person in charge) must determine the answers to a number of questions, such as

1. Does a potable water supply exist nearby that has the capacity for water to be distributed in sufficient quantity and pressure at all times?
2. Will constructing a centralized treatment and distribution system for the entire community be best, or would using individual well supplies be better?
3. If a centralized water treatment facility is required, will the storage capacity at the source as well as at intermediate points of the distribution system maintain the water pressure and flow (quantity) within the conventional limits, particularly during loss-of-pressure events, such as major water main breaks, rehabilitation of the existing system, or major fires, for example?

4. Is a planned or preventive maintenance program in place (or anticipated) for the distribution system that can be properly planned, implemented, and controlled at the optimum level possible?
5. Is the type of water treatment process selected in compliance with federal and state drinking water standards? Note: Water from a river or a lake usually requires more extensive treatment than groundwater does to remove bacteria and suspended particles. Note: The primary concern for drinking water practitioners involved with securing an appropriate water supply, treatment process, and distribution system must be the protection of public health. Contaminants must be eliminated or reduced to a safe level to minimize menacing waterborne diseases (to prevent another Milwaukee Cryptosporidium event) and to avoid long-term or chronic injurious health effects.
6. When the source and treatment processes are selected, has the optimum hydraulic design of the storage, pumping, and distribution network been determined to ensure that sufficient quantities of water can be delivered to consumers at adequate pressures?
7. Have community leaders and the consumer (the general public) received continuing and realistic information about the functioning of the proposed drinking water service? Note: Drinking water practitioners are wise to direct their attention toward considering point 7, simply because public buy-in for any proposed drinking water project that involves new construction or retrofitting, expansion, or upgrade of an existing facility is essential to ensure that necessary financing is forthcoming. In addition to the finances required for any type of waterworks construction project, public and financial support is also required to ensure the safe operation, maintenance, and control of the entire water supply system. The acronym POTW stands for “publicly owned treatment works,” and the public foots the bills.
8. Does planning include steps to ensure elimination of waste, leakages, and unauthorized consumption? Note: Industrywide operational experience has shown that the cost per cubic foot, cubic meter, liter, or gallon of water delivered to the customer has steadily increased because of manpower, automation, laboratory, and treatment costs. To counter these increasing costs, treatment works must meter consumers, measure the water supply flow, and evaluate the entire system annually.
9. Does the water works or proposed water works physical plant include adequate laboratory facilities to ensure proper monitoring of water quality? Note: Some water works facilities routinely perform laboratory work; however, water pollution control technologists must ensure that the water works laboratory or other laboratory used is approved by the appropriate health authority. Keep in mind that the laboratory selected to test and analyze the waterworks samples must be able to analyze chemical, microbiologic, and radionuclide parameters.
10. Are procedures in place to evaluate specific problems such as the lead content in the distribution systems and at the consumer’s faucet or suspected contamination due to cross-connection potentials?
11. Is a cross-connection control program in place to make sure that the distribution system (in particular) is protected from plumbing errors and illegal connections that may lead to injection of non-potable water into public or private supplies of drinking water?

12. Are waterworks operators and laboratory personnel properly trained and licensed?
13. Are waterworks managers properly trained and licensed?
14. Are proper operating records and budgetary records kept?

DRINKING WATER Q AND Q: KEY DEFINITIONS As with any other technical presentation, understanding the information presented is difficult unless a common vocabulary is established. Voltaire said it best: “If you wish to converse with me, please define your terms.” Many key terms used in the text are defined in this section, but others are defined where they appear in the text. Before defining these key terms, however, it is necessary to first define the key term that this text is all about: drinking water. Drinking, or potable, water can be defined as the water delivered to the consumer that can be safely used for drinking, cooking, washing, and other household applications. In the past, drinking water suitable for use (i.e., safe) was simply certified as safe by a professional engineer specialized in the field, but times have changed. This practice is no longer accepted. Why? Because public health aspects have reached such a high level of importance and complexity that local licensed health officials usually must be designated as those with the authority and jurisdiction in the community to review, inspect, sample, monitor, and evaluate the water supplied to a community on a continuing basis. This professional scrutiny is driven by updated drinking water standards, of course. When you factor in the importance of providing a safe, palatable product to the public, the fact that public health control is required to help ensure a continuous supply of safe drinking water makes real sense. On many occasions, drinking water practitioners have attempted to explain to interested parties the complexities of providing safe drinking water to their household taps. Of course, such practitioners know that the process is complex but still continue to be surprised when listeners express astonishment at the complex procedures and processes involved. It becomes readily apparent that a commonly held view is that the provision of drinking water to the consumer tap involves nothing more than going down to the local river or stream, installing a suction pipe into the watercourse, and pumping the water out and into a distribution network that somehow delivers clean, safe drinking water to the household tap. Yes, water often is taken from a local river or stream, and that water does eventually find its way to the household tap. However (isn’t there always a “however” in any explanation?), the water drawn from any local surface water supply must pass through certain processes to ensure its wholesomeness and safety. Aside from the physical treatment processes in place to screen, filter, and disinfect the water, additional processes include continually inspecting, sampling, monitoring, and evaluating the water supply. Drinking water practitioners learn the ins and outs of drinking water primarily from experience. The main lesson learned is that supplying drinking water to the household tap is a complex and demanding process; for example, it is obvious that water analysis is required but it alone is not sufficient to maintain quality. It must be combined with the periodic review and acceptance of the facilities involved. What does this mean? Simply stated, acceptance or approval requires evaluation, maintenance, and proper protection of the water source; qualified waterworks personnel; adequate monitoring procedures by water suppliers; and evaluation of the quality and performance of laboratory work (DeZuane, 1997). Thus, when we attempt to define drinking water, we must define it in all-encompassing terms. Drinking or potable water is a product from an approved source that falls within certain physical, chemical, bacteriological, and radionuclide parameters and is delivered to a treatment works for processing and disinfecting. Such a treatment works must be properly designed, constructed, and operated. Drinking water must be delivered to

the consumer in sufficient quantity and pressure and must meet stringent quality standards. It must be palatable, be within reasonable temperature limits, and have the complete confidence of the consumer. The bottom line is that drinking water is a substance available to the consumer at the household tap that can perform one essential function: It can satisfy thirst without threatening life and health.

Definitions Absorption—A process where one substance penetrates the interior of another substance. Acid rain—Precipitation with higher than normal acidity, caused primarily by sulfur and nitrogen dioxide air pollution. Activated carbon—A very porous material that can be used to adsorb pollutants from water after the material has been subjected to intense heat to drive off impurities. Adsorption—The process by which one substance is attracted to and adheres to the surface of another substance, without actually penetrating its internal structure. Aeration—A physical treatment method that promotes biological degradation of organic matter. The process may be passive (when waste is exposed to air) or active (when a mixing or bubbling device introduces air). Aerobic bacteria—A type of bacteria that requires free oxygen to carry out metabolic function. Biochemical oxygen demand (BOD)—The amount of oxygen required by bacteria to stabilize decomposable organic matter under aerobic conditions. Biological treatment—A process that uses living organisms to bring about chemical changes. Breakpoint chlorination—The addition of chlorine to water until the chlorine demand has been satisfied and free chlorine residual is available for disinfection. Chemical treatment—A process that results in the formation of a new substance or substances. The most common chemical water treatment processes include coagulation, disinfection, water softening, and filtration. Chlorination—The process of adding chlorine to water to kill disease-causing organisms or to act as an oxidizing agent. Chlorine demand—A measure of the amount of chlorine that will combine with impurities and is therefore unavailable to act as a disinfectant. Clean Water Act (CWA)—Federal law dating to 1972 (with several amendments) with the objective to restore and maintain the chemical, physical, and biological integrity of the nation's waters. Its long-range goal is to eliminate the discharge of pollutants into navigable waters and to make national waters fishable and swimmable. Coagulants—Chemicals that cause small particles to stick together to form larger particles. Coagulation—A chemical water treatment method that causes very small suspended particles to attract one another and form larger particles. This is accomplished by the addition of a coagulant that neutralizes the electrostatic charges that cause particles to repel each other. Coliform bacteria—A group of bacteria predominantly inhabiting the intestines of humans or animals, but also occasionally found elsewhere. The presence of these bacteria in water is used as an indication of fecal contamination (contamination by animal or human wastes). Color—A physical characteristic of water. Color is most commonly tan or brown from oxidized iron, but contaminants may cause other colors, such as green or blue. Color differs from turbidity, which is a measure of the cloudiness of the water. Communicable diseases—Usually caused by microbes, which are microscopic organisms including bacteria, protozoa, and viruses. Most microbes are essential components of our environment and do not cause disease. Those that do are called pathogenic organisms, or simply pathogens.

Community water system—A public water system that serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents. Composite sample—A series of individual or grab samples taken at different times from the same sampling point and mixed together. Contaminant—A toxic material found as an unwanted residue in or on a substance. Cross-connection—Any connection between safe drinking water and a nonpotable water or fluid. C×T value—The product of the residual dis-

infectant concentration (C), in milligrams per liter, and the corresponding disinfectant contact time (T), in minutes. Minimum $C \times T$ values are specified by the Surface Water Treatment Rule as a means of ensuring adequate killing or inactivation of pathogenic microorganisms in water. Disinfectants and disinfection byproducts (DBPs)—A term used in connection with state and federal regulations designed to protect public health by limiting the concentration of either disinfectants or the byproducts formed by the reaction of disinfectants with other substances in the water (such as trihalomethanes, THMs). Disinfection—A chemical treatment method; the addition of a substance (e.g., chlorine, ozone, hydrogen peroxide) that destroys or inactivates harmful microorganisms or inhibits their activity. Dissociation—The process of ion separation that occurs when an ionic solid is dissolved in water. Dissolved oxygen (DO)—The oxygen dissolved in water, usually expressed in milligrams per liter, parts per million, or percent of saturation. Dissolved solids—Any material that can dissolve in water and be recovered by evaporating the water after filtering the suspended material. Drinking water standards—Water quality standards that must be met in terms of suspended solids, unpleasant taste, and microbes harmful to human health. Drinking water standards are included in state water quality rules. Drinking water supply—Any raw or finished water source that is or may be used as a public water system or as drinking water by one or more individuals. Effluent limitations—Standards developed by the U.S. Environmental Protection Agency (USEPA) to define the levels of pollutants that could be discharged into surface waters. Electrodialysis—The process of separating substances in a solution by dialysis, using an electric field as the driving force. Electronegativity—The tendency for atoms that do not have a complete octet of electrons in their outer shell to become negatively charged. Enhanced Surface Water Treatment Rule (ESWTR)—A revision of the original Surface Water Treatment Rule that includes new technology and requirements to deal with newly identified problems. Facultative bacteria—A type of anaerobic bacteria that can metabolize its food either aerobically or anaerobically.

Federal Water Pollution Control Act (1972)—The objective of the Act was “to restore and maintain the chemical, physical, and biological integrity of the nation’s waters.” This Act and subsequent Clean Water Act amendments are the most far-reaching water pollution control legislation ever enacted. They provide for comprehensive programs for water pollution control, uniform laws, and interstate cooperation, as well as grants for research, investigation, training, surveillance, and gathering information on the effects of pollutants, pollution control, and the identification and measurement of pollutants. Additionally, they allot grants and loans for the construction of treatment works. The Act established national discharge standards with enforcement provisions and established several milestone achievement dates. It required secondary treatment of domestic waste by publicly owned treatment works (POTW) and the application of “best practicable” water pollution control technology by 1977. Virtually all industrial sources achieved compliance. (Because of economic difficulties and cumbersome federal requirements, certain POTWs obtained an extension to July 1, 1988, to achieve compliance.) The Act also called for new levels of technology to be imposed during the 1980s and 1990s, particularly for controlling toxic pollutants. The Act mandates a strong pretreatment program to control toxic pollutants discharged by industry into POTWs. The 1987 amendments required that stormwater from industrial activity must be regulated. Filtration—A physical treatment method for removing solid (particulate) matter from water by passing the water through porous media such as sand or a manmade filter. Flocculation—The water treatment process following coagulation; it uses gentle stirring to bring suspended particles together so they will form larger,

more settleable clumps called floc. Grab sample—A single water sample collected at one time from a single point. Groundwater—The freshwater found under the Earth's surface, usually in aquifers. Groundwater is a major source of drinking water and a source of growing concern in areas where leaching agricultural or industrial pollutants or substances from leaking underground storage tanks are contaminating groundwater. Hardness—A characteristic of water caused primarily by the salts of calcium and magnesium. It leads to the deposition of scale in boilers, damages equipment in industrial processes, and sometimes causes an objectionable taste. It may also decrease the effectiveness of soap. Hydrogen bonding—The term used to describe the weak but effective attraction that occurs between polar covalent molecules. Hydrologic cycle—Literally the water–Earth cycle; the movement of water in all three physical forms through the various environmental mediums (air, water, biota, and soil). Hygroscopic—Refers to a substance that readily absorbs moisture. Influent—Water flowing into a reservoir, basin, or treatment plant. Inorganic chemical—A chemical substance of mineral origin not having carbon in its molecular structure. Ionic bond—The attractive forces between oppositely charged ions—for example, the forces between sodium and chloride ions in a sodium chloride crystal. Maximum contaminant level (MCL)—The maximum allowable concentration of a contaminant in drinking water, as established by state and federal regulations. Primary MCLs are health related and mandatory. Secondary MCLs are related to the aesthetics of the water and are highly recommended, but not required. Membrane filter method—A laboratory method used for coliform testing. The procedure uses an ultrathin filter with a uniform pore size smaller than bacteria (less than 1 micron). After water is forced through the filter, the filter is incubated in a special medium that promotes the growth of coliform bacteria. Bacterial colonies with a green–gold sheen indicate the presence of coliform bacteria. Modes of transmission of disease—The ways in which diseases spread from one person to another. Multiple-tube fermentation method—A laboratory method used for coliform testing that uses a nutrient broth placed in a culture tube. Gas production indicates the presence of coliform bacteria. National Pollutant Discharge Elimination System (NPDES)—A requirement of the CWA that discharges meet certain requirements prior to discharging waste to any water body. It sets the highest permissible effluent limits, by permit, prior to making any discharge. National Primary Drinking Water Regulations (NPDWRs)—Regulations developed under the Safe Drinking Water Act that establish maximum contaminant levels, monitoring requirements, and reporting procedures for contaminants in drinking water that endanger human health. Near Coastal Water Initiative—An initiative that was developed in 1985 to provide for the management of specific problems in waters near coastlines that are not dealt with in other programs. Nonbiodegradable—Refers to substances that do not break down easily in the environment. Nonpolar covalently bonded—Refers to molecules composed of atoms that share their electrons equally, resulting in molecules that do not have polarity. Organic chemical—A chemical substance of animal or vegetable origin having carbon in its molecular structure. Oxidation—Occurs when a substance either gains oxygen or loses hydrogen or electrons in a chemical reaction; one of the chemical treatment methods. Oxidizer—A substance that oxidizes another substance. Parts per million (PPM)—The number of weight or volume units of a constituent present within each 1 million units of the solution or mixture. PPM was formerly used to express the results of most water and wastewater analyses, but it is being replaced by milligrams per liter (mg/L). For drinking water analyses, concentration in parts per million and milligrams per liter can be considered to be equivalent. A single PPM can be compared to a shot glass full of water inside a swimming pool. Pathogens—Types of microorganisms that can cause disease.

Physical treatment—Any process that does not produce a new substance (e.g., screening, adsorption, aeration, sedimentation, filtration). **Polar covalent bond**—Occurs when the shared pair of electrons between two atoms are not shared equally; thus, one of the atoms becomes slightly positively charged and the other atom becomes slightly negatively charged. **Polar covalent molecule**—One or more polar covalent bonds result in a molecule that is polar covalent. Polar covalent molecules exhibit partial positive and negative poles, causing them to behave like tiny magnets; water is the most common polar covalent substance. **Pollutant**—Any substance introduced into the environment that adversely affects the usefulness of the resource. **Pollution**—The presence of matter or energy whose nature, location, or quantity produces undesired environmental effects. Under the Clean Water Act, for example, the term is defined as a manmade or human-induced alteration of the physical, biological, and radiological integrity of water. **Pretreatment**—Any physical, chemical, or mechanical process used before the main water treatment processes. It can include screening, pre-sedimentation, and chemical addition. **Primary drinking water standards**—Regulations on drinking water quality defined under the Safe Drinking Water Act that are considered essential for the preservation of public health. **Primary treatment**—The first step of treatment at a municipal wastewater treatment plant. It typically involves screening and sedimentation to remove materials that float or settle. **Public water system (PWS)**—As defined by the Safe Drinking Water Act, any publicly or privately owned system serving at least 15 service connections 60 days out of the year or an average of 25 people at least 60 days out of the year. **Publicly owned treatment works (POTW)**—A waste treatment works owned by a state or local government unit or Indian tribe, usually designed to treat domestic wastewaters. **Receiving water**—A river, lake, ocean, stream, or other water source into which wastewater or treated effluent is discharged. **Recharge**—The process by which water is added to a zone of saturation, usually by percolation from the soil surface. **Reference dose (RfD)**—An estimate of the amount of a chemical that a person can be exposed to on a daily basis that is not anticipated to cause adverse systemic health effects over the person's lifetime. **Representative sample**—A sample containing all the constituents present in the water from which it was taken. **Reverse osmosis (RO)**—Solutions of differing ion concentration are separated by a semipermeable membrane. Typically, water flows from the chamber with lesser ion concentration into the chamber with the greater ion concentration, resulting in hydrostatic or osmotic pressure. In RO, enough external pressure is applied to overcome this hydrostatic pressure, thus reversing the flow of water. This results in the water on the other side of the membrane becoming depleted in ions and demineralized. **Safe Drinking Water Act (SDWA)**—A federal law passed in 1974 with the goal of establishing federal standards for drinking water quality, protecting underground sources of water, and setting up a system of state and federal cooperation to ensure compliance with the law. **Screening**—A pretreatment method that uses coarse screens to remove large debris from the water to prevent clogging of pipes or channels to the treatment plant. **Secondary drinking water standards**—Regulations developed under the Safe Drinking Water Act that established maximum levels of substances affecting the aesthetic characteristics (taste, color, or odor) of drinking water. **Secondary treatment**—The second step of treatment at a municipal wastewater treatment plant. This step uses growing numbers of microorganisms to digest organic matter and reduce the amount of organic waste. Water leaving this process is chlorinated to destroy any disease-causing microorganisms before its release. **Sedimentation**—A physical treatment method that involves reducing the velocity of water in basins so the suspended material can settle out by gravity. **Solvated**—Refers to when either a positive or a negative ion becomes completely surrounded by polar solvent molecules. **Sur-**

face tension—The attractive forces exerted by the molecules below the surface upon those at the surface, resulting in them crowding together and forming a higher density. Surface water—All water naturally open to the atmosphere; all springs, wells, or other collectors that are directly influenced by surface water. Surface Water Treatment Rule (SWTR)—A federal regulation established by the USEPA under the Safe Drinking Water Act that imposes specific monitoring and treatment requirements on all public drinking water systems that draw water from a surface water source. Synthetic organic chemicals (SOCs)—Generally applied to manufactured chemicals that are not as volatile as volatile organic chemicals. Included are herbicides, pesticides, and chemicals widely used in industries. Total suspended solids (TSS)—Solids present in wastewater. Trihalomethanes (THMs)—A group of compounds formed when natural organic compounds from decaying vegetation and soil (such as humic and fulvic acids) react with chlorine. Turbidity—A measure of the cloudiness of water caused by the presence of suspended matter, which shelters harmful microorganisms and reduces the effectiveness of disinfecting compounds. Vehicle of disease transmission—Any nonliving object or substance contaminated with pathogens. Wastewater—The spent or used water from individual homes, a community, a farm, or an industry that contains dissolved or suspended matter. Waterborne disease—Water is a potential vehicle of disease transmission, and waterborne disease is possibly one of the most preventable types of communicable illness. The application of basic sanitary principles and technology has virtually eliminated serious outbreaks of waterborne diseases in developed countries. The most prevalent waterborne diseases include typhoid fever, dysentery, cholera, infectious hepatitis, and gastroenteritis. Note: Waterborne diseases are also called intestinal diseases, because they affect the human intestinal tract. If pathogens excreted in the feces of infected people are inadvertently ingested by others (in contaminated water, for example), the cycle of disease can continue, possibly in epidemic proportions. Symptoms of intestinal disease include diarrhea, vomiting, nausea, and fever. Intestinal diseases can incapacitate large numbers of people in an epidemic and sometimes result in the deaths of many infected individuals. Water contaminated with untreated sewage is generally the most common cause of this type of disease (Nathanson, 1997). In practice, “hazard identification in the case of pathogens is complicated because several outcomes—from asymptomatic infections to death—are possible, and their outcomes depend upon the complex integration between the agent and the host. This interaction, in turn, depends on the characteristics of the host as well as the nature of the pathogen. Host factors, for example, include preexisting immunity, age, nutrition, ability to mount an immune response, and other nonspecific host factors. Agent factors include types and strains of the organism as well as its capacity to elicit an immune response” (Gerba, 1996). Water softening—A chemical treatment method that uses either chemicals to precipitate or a zeolite to remove the metal ions (typically Ca^{2+} , Mg^{2+} , and Fe^{3+}) responsible for hard water. Watershed—The land area that drains into a river, river system, or other body of water. Wellhead protection—The protection of the surface and subsurface areas surrounding a water well or well field supplying a public water system from contamination by human activity.

CLEAN, FRESH, AND PALATABLE: A HISTORICAL PERSPECTIVE An early human, wandering alone from place to place, hunting and gathering to subsist, probably would have had little difficulty in obtaining drinking water, because such a person would—and could—only survive in an area where drinking water was available with little travail. The search for clean, fresh, and palatable water has been a human priority from the very beginning. The author is taking no risk in stating that when humans first walked the Earth many of the steps they took were in the direction of a water supply. When early humans were

alone or gathered in small numbers, finding drinking water was a constant priority, to be sure, but it is difficult for us to imagine today just how big a priority finding drinking water became as the number of humans proliferated. Eventually communities formed, and with their formation came an increasing need to find clean, fresh, and palatable drinking water, as well as a means of delivering it from the source to the point of use. Archeological digs are replete with the remains of ancient water systems that reflect humans' early attempts to satisfy their never-ending need for drinking water. For well over 2000 years, piped water supply systems have been in existence. Whether the pipes were fashioned from logs or clay or carved from stone or other

materials is not the point—the point is they were fashioned to serve a vital purpose, one universal to all human communities: to deliver clean, fresh, and palatable water to where it was needed. These early systems were not arcane. Their intended purpose is readily understood today. As we might expect, they could be rather crude, but they were reasonably effective, although they lacked in two general areas we take for granted today. First, of course, they were not pressurized but instead relied on gravity flow, as the means to pressurize the mains was not known at the time. Even if such pressurized systems were known, they certainly would not have been used to pressurize water delivered via hollowed-out logs and clay pipe. The second general area in which they lacked was sanitation, which is generally taken for granted by those in the industrialized world of today. Remember, to recognize that a need for something exists (in this case, the ability to sanitize or disinfect water supplies), it is necessary to define the nature of the problem. Not until the middle of the 1800s (after countless millions of deaths from waterborne disease over the centuries) did people realize that a direct connection between contaminated drinking water and disease existed. At that point, sanitation of water supplies became an issue. When the relationship between waterborne diseases and the consumption of drinking water was established, evolving scientific discoveries led the way toward development of the technology necessary for processing and disinfection. Drinking water standards were developed by health authorities, scientists, and sanitary engineers. With the current lofty state of effective technology that we in the United States and the rest of the developed world enjoy today, we could sit on our laurels, so to speak, and assume that because of the discoveries developed over time (at the cost of countless people who died and are still dying from waterborne diseases), all is well with us—that problems related to providing a clean, fresh, palatable drinking water are problems of the past. Are they really, though? Have we solved all the problems related to ensuring that our drinking water is clean, fresh, and palatable? Is the water delivered to our tap as clean, fresh, and palatable as we think it is ... as we hope it is? Does anyone really know? What we do know is that we have made progress. We have come a long way from the days of gravity-flow water delivered via mains of logs and clay or stone, and many of us on this planet have come a long way from the days of cholera epidemics. Still, perhaps we should consider those who have suffered and survived onslaughts of *Cryptosporidium* delivered to them through their tap—in Sydney, Australia, in 1998; in Milwaukee, Wisconsin, in 1993; in Las Vegas, Nevada, in the early 1990s. How safe do they think our drinking water supply is? If we could, we would ask this same question of a little boy named Robbie, who died of acute lymphatic leukemia, the probable cause of which is far less understandable to us: toxic industrial chemicals, unknowingly delivered to him via his local water supply.

Drinking Water Regulations Drinking water regulations have undergone major and dramatic changes during the past two decades, and trends indicate that they will continue to become more stringent and com-

plicated. It is important that all water system operators understand the basic reasons for having regulations, how they are administered, and why compliance with them is so essential. AWWA (2005)

Indeed, the 2010 volume of the Federal Register, the “newspaper” of regulatory agencies, stands at an all-time record-high 81,405 pages composed of final rules, proposed rules, meeting notices and regulatory studies. “There is something like 180 million words of binding federal law and regulation. It would take a lifetime just to read it,” said Philip K. Howard, founder of Common Good. Fox News (2011)

Some say we are a Regulation Nation. To a point we fully agree with this statement . . . and in most cases we feel these narrow-minded rules and regs are adverse and stymieing economic progress . . . which is sorely lacking at present. Again, we feel this way to a point. However, there is no point reached when it comes to maintaining personal safety and health. Thus, if we have to be a Regulation Nation to ensure the tap water we drink is clean, safe, and palatable then we say, “Please, regulate to the extreme, thank you very much!”

REGULATION NATION As stated above, many consider us to be a Regulation Nation. A 2011 Fox News story pointed out that, even though President Obama had acknowledged the need to minimize regulations, the number appeared to be growing. The Obama administration introduced regulations at a rate equivalent to 10 per week. Whether the reader believes this is good or bad practice is not the point. The point is that adapting the workforce to the challenges of constantly changing regulations and standards for water treatment is a major concern. Drinking water standards are regulations that the U.S. Environmental Protection Agency (USEPA) sets to control the level of contaminants in the nation’s drinking water. These standards are part of the Safe Drinking Water Act’s multiple-barrier approach to drinking water protection. Why do we need regulations? Most of us, having no taste for anarchy, would have little trouble answering this question. We regulate ourselves and others for a variety of reasons, but in our attempts to do so we generally strive to attain similar results. Most governments, for example, regulate their population to provide direction, to manage, to monitor, and to literally govern whatever it is they are attempting to regulate (including us). We also regulate to confine, to control, to limit, and to restrict ourselves within certain parameters to maintain the peace—with the goal of providing equal and positive social conditions for us all. Regulations are not foreign to us . . . we are literally driven by them from birth through our final internment—you could say that we are literally regulated to death. Some regulations are straightforward. The 70-mph speed limit on some interstates is simple—the regulation establishes measurable limits. Other regulations are not so simple, such as regulations designed to ensure the safe and correct operation of nuclear reactors that are complex and difficult to meet. Whether straightforward or complex, however, enforcement presents special problems. As to safe drinking water regulations, we can only hope that the regulations in place to ensure our safety and health are more effectively enforced than that 70-mph speed limit. In this chapter, we discuss U.S. federal regulations designed to protect our health and well-being: the so-called drinking water regulations. Control of the quality of our drinking water is accomplished by establishing certain regulations, which in turn require compliance within an established set of guidelines or parameters. The guidelines are the regulations themselves; the parameters are the water quality factors important to providing drinking water that is safe and palatable.

WHY REGULATE? Consider what might be an absurd question: “Why do we need to regulate water quality?” And another question that is perhaps a bit more logical: “Aren’t we already regulated enough?” The first question requires a compound answer, the explanation of which is provided in this chapter—in

the hope that it will clear the water, so to speak. The second question? This question must be answered with another question: “When it comes to ensuring a safe and palatable drinking water supply, are we (or can we be) regulated enough?” This text concentrates on answering the first question because it goes to the heart of our discussion—the necessity of providing safe and palatable drinking water to the user. Again, why do we need to regulate water quality? Let’s start at the beginning. In the beginning (the ancient beginning), humans really had no reason to give water quality much of a thought. Normally, nearly any water supply available was only nominally naturally polluted. Exceptions existed of course; for example, a prehistoric human flattened out on the ground alongside a watercourse to drink would not ingest too much of the water (as little of it as possible, in fact) if it was salty. Our intrepid (but thirsty) ancestor would probably move on to find another water source, one a bit more palatable. Determining water’s fitness to drink was a matter of sight, smell, and a quick taste. If the relevant criteria were met, the water was used. Our early kinfolk were likely to have gulped down water that looked perfectly clear, smelled all right, and did not taste all that bad. Later that day, though, the water could have made them sick, very sick—sickened by waterborne pathogens that were residents of that perfectly clear, not too bad tasting water ingested a few hours earlier. Of course, early humans would not have had the foggiest notion what caused the sickness, but they would have become very sick, indeed. Let’s take a look at more recent times, at another scenario that helps illustrate the point that we are making here (Spellman, 1996): An excursion to the local stream can be a relaxing and enjoyable undertaking. On the other hand, when you arrive at the local stream, spread your blanket on the stream bank, and then look out upon the stream’s flowing mass only to discover a parade of waste and discarded rubble bobbing along the stream’s course and cluttering the adjacent shoreline and downstream areas, any feeling of relaxation or enjoyment is quickly extinguished. Further, the sickening sensation the observer feels is not lessened but made worse as he gains closer scrutiny of the putrid flow. He easily recognizes the rainbow-colored shimmer of an oil slick, interrupted here and there by dead fish and floating refuse, and the slimy fungal growth that prevails. At the same time, the observer’s sense of smell is alerted to the noxious conditions. Along with the fouled water and the stench of rot-filled air, the observer notices the ultimate insult and tragedy: The signs warn: “DANGER—NO SWIMMING or FISHING.” The observer soon realizes that the stream before him is not a stream at all; it is little more than an unsightly drainage ditch. The observer has discovered what ecologists have known and warned about for years. That is, contrary to popular belief, rivers and streams do not have an infinite capacity for pollution.

This relatively recent scenario makes an important point for us: The qualities of water that directly affect our senses are the first to disturb us. This certainly was the case with ancient humans, before the discovery of what causes disease and waterborne disease in particular. Even before the mid-1850s, when Dr. John Snow, in London, made the connection between water and disease (i.e., the waterborne disease cholera), rumblings could be heard in that city about the terribly polluted state of the Thames River. Dr. Snow’s discovery of the connection between cholera and drinking water obtained from the Broad Street pump that was ingested by those who became ill or died lit the fire of reform, and revulsion set in motion steps to clean up the water supply. Since Snow’s discovery, many subsequent actions taken to clean up a particular water supply resulted from incidents related to public disgust with the sorry state of the watercourse. For example, in the 1960s, the burgeoning environmental movement found many ready examples of the deplorable state and vulnerability of America’s waters. In Cleveland, the Cuyahoga River burst into

flames, so polluted was it with chemicals and industrial wastes; historic Boston Harbor was a veritable cesspool; raw sewage spewed into San Francisco Bay. A 1969 oil spill off scenic Santa Barbara, California, proved an especially telegenic disaster due to the resulting oil-soaked seals and pelicans and miles of hideously fouled beaches. These and other incidents were disturbing to many Americans and brought calls for immediate reform. Awareness of the state of our environment was at an all-time high. A grassroots crusade for environmental action was set into motion by the words of a brilliant writer, a writer whose penetrating scientific views and poetic prose captured the imagination of the nation. Rachel Carson became the flag bearer for our environment. By making the connections between isolated incidents and the actions of industry, research, and government, she brought the clear light of day into the dark abyss of environmental degradation, revealing widespread horrible environmental conditions and the future they could lead to. The public lost trust in the ability of government and industry to self-govern with regard to choosing between money and the benefits of a clean environment for us all. Industry and government's close connections and financial self-interest were revealed as poor criteria for determining realistic levels of environmental protection. With Rachel Carson's *Silent Spring* came the sobering awareness that environmental conditions and the prevailing governmental attitude demanded radical change. Individual incidents disturbed many Americans to the point that they demanded immediate reforms.

CLEAN WATER REFORM IS BORN To understand the history (and thus the impetus) behind the reform movement intent on cleaning up our water supplies, we can trace a chronology of some of the significant events precipitated by environmental organizations and citizens groups that have occurred since the mid-1960s:*

1. Americans came face-to-face with the grim condition of the nation's waterways in 1969, when the industrial-waste-laden Cuyahoga River caught on fire. That same year, waste from food-processing plants killed almost 30 million fish in Lake Thonotosassa, Florida.
2. In 1972, Congress enacted the Clean Water Act (after having overridden President Nixon's veto). The passage of the Clean Water Act has been called "literally a life-or-death proposition for the nation." The Act set the goals of achieving water that is "fishable and swimmable" by 1983 and zero discharges of pollutants by 1985, in addition to prohibiting the discharge of toxic pollutants in toxic amounts.
3. In 1974, the Safe Drinking Water Act (SDWA) was passed, requiring the U.S. Environmental Protection Agency (USEPA) to establish national standards for contaminants in drinking water systems, underground wells, and sole-source aquifers, in addition to several other requirements.
4. In 1984, an alliance of the Natural Resources Defense Council, the Sierra Club, and others successfully sued Phillips ECG, a New York industrial polluter that had dumped waste into the Seneca River. According to the Sierra Club's water committee chair, Samuel Sage, the case "tested the muscles of citizens against polluters under the Clean Water Act." During this same timeframe, a Clean Water Act reauthorization bill drew the wrath of environmental groups, who dubbed it the "Dirty Water Act" after lawmakers added last-minute pork and weakened wetland protection and industrial pretreatment provisions. Grassroots action led to most of these pork provisions being dropped. That same year also saw the highest environmental penalty to date—\$70,000, which was imposed on Alcoa

Aluminum in Messina, New York (for polluting the St. Lawrence River), as a result of a suit filed by the Sierra Club.

5. In 1986, Tip O'Neill, Speaker of the House of Representatives, stated that he would not let a Clean Water Act reauthorization bill on the floor without the blessing of environmental groups. Later, after the bill was crafted and passed by Congress, President Reagan vetoed the bill. Also in 1986, amendments to the Safe Drinking Water Act directed the USEPA to publish a list of drinking water contaminants that require legislation.
6. In 1987, the Clean Water Act was reintroduced. It became law after Congress overrode President Reagan's veto. A new provision established the National Estuary Program.
7. From 1995 to 1996, the House passed H.R. 961 (again dubbed the "Dirty Water Act"), which in some cases eliminated standards for water quality, wetlands protection, sewage treatment, and agricultural and urban runoff. The Sierra Club collected over 1 million signatures in support of the Environmental Bill of Rights and released "Danger on Tap," a report that revealed polluter contributions to friends in Congress who wanted to gut the Clean Water Act. Due in part to these efforts, the bill was stopped in the Senate.
8. In 1997, the USEPA reported that more than a third of the country's rivers and half of its lakes were still unfit for swimming or fishing. The Sierra Club successfully sued the USEPA to enforce Clean Water Act regulations in Georgia. The state was required to identify polluted waters and establish their pollution-load capacity. Similar suits were filed in other states; for example, in Virginia, Smithfield Foods was assessed a penalty of more than \$12 million—the highest ever—for violating the Clean Water Act by discharging phosphorus and other hog waste products into a tributary of the Chesapeake Bay.

This chronology of events presents only a handful of the significant actions taken by Congress (with the helpful prodding and guidance of the Sierra Club and the National Resources Defense Council, as well as others) in enacting legislation and regulations to protect our nation's waters. No law has been more important to furthering this effort than the Clean Water Act, which we discuss in the following section.

CLEAN WATER ACT* Concern with the disease-causing pathogens residing in many of our natural waterways was not what grabbed Joe and Nancy Citizen's attention with regard to the condition and health of the country's waterways. Instead, it was the aesthetic qualities of watercourses. Americans in general have a strong emotional response to the beauty of nature, and they acted to prevent pollution and degradation of our nation's waterways simply because many of us expect rivers, waterfalls, and mountain lakes to be natural and naturally beautiful—in the state they were intended to be, pure and clean.

Much of this emotional attachment to the environment can be traced back to the sentimentality characteristic of the popular literature and art of American writers and painters in the early 19th century. From Longfellow's *Song of Hiawatha* to Twain's *Huckleberry Finn* to the landscapes of Winslow Homer and the vistas of the Hudson River School painters, American culture abounds with expressions of this singularly strong attachment. As the saying goes: "Once attached, detachment is never easy." Federal water pollution legislation dates back to the turn of the century, to the Rivers and Harbors Act of 1899, although

the Clean Water Act stems from the Federal Water Pollution Control Act, which was originally enacted in 1948 to protect surface waters such as lakes, rivers, and coastal areas. That act was significantly expanded and strengthened in 1972 in response to growing public concern over serious and widespread water pollution problems. The 1972 legislation provided the foundation for our dramatic progress in reducing water pollution over the past several decades. Amendments to the 1972 Clean Water Act were made in 1977, 1981, and 1987. The Clean Water Act focuses on improving water quality by maintaining and restoring the physical, chemical, and biological integrity of the nation's waters. It provides a comprehensive framework of standards, technical tools, and financial assistance to address the many stressors that can cause pollution and adversely affect water quality, including municipal and industrial wastewater discharges, polluted runoff from urban and rural areas, and habitat destruction. The Clean Water Act requires national performance standards for major industries (such as iron and steel manufacturing and petroleum refining) that provide a minimum level of pollution control based on the best technologies available. These national standards result in the removal of over a billion pounds of toxic pollution from our waters every year. The Clean Water Act also establishes a framework whereby states and Indian tribes survey their waters, determine an appropriate use (such as recreation or water supply), then set specific water quality criteria for various pollutants to protect those uses. These criteria, together with the national industry standards, are the basis for permits that limit the amount of pollution that can be discharged to a water body. Under the National Pollutant Discharge Elimination System (NPDES), sewage treatment plants and industries that discharge wastewater are required to obtain permits and to meet the specified limits in those permits. Note: The Clean Water Act requires the USEPA to set effluent limitations. All dischargers of wastewaters to surface waters are required to obtain NPDES permits, which require regular monitoring and reporting. The Clean Water Act also provides federal funding to help states and communities meet their clean water infrastructure needs. Since 1972, federal funding has provided billions of dollars in loans and grants, primarily for building or upgrading wastewater treatment plants. In 2015, for example, \$314 million in loans and grants became available for 141 projects to build and improve water and wastewater infrastructure in rural communities (USDA, 2015). Funding is also provided to address another major water quality problem—polluted runoff from urban and rural areas. Protecting valuable aquatic habitat—wetlands, for example—is another important component of this law. American waterways have suffered loss and degradation of biological habitat, a widespread cause of the decline in the health of aquatic resources. When Europeans colonized this continent, North America held approximately 221 million acres of wetlands. Today, most of those wetlands are gone. At least 22 states have lost 50% or more of their original acreage of wetlands, and 10 states have lost about 70% of their wetlands. The Clean Water Act sections dealing with wetlands have become extremely controversial. Wetlands are among our nation's most fragile ecosystems and play a valuable role in maintaining regional ecology and preventing flooding, while serving as home to numerous species of insects, birds, and animals; however, wetlands also represent significant potential monetary value in the eye of private landowners and developers. Herein lies the major problem. Many property owners feel they are being unfairly penalized by a Draconian regulation that restricts their right to develop their own property. Alternative methods that do not involve destroying the wetlands are available. These methods include wetlands mitigation and mitigation banking. Since 1972, when the Clean Water Act was passed, permits from the U.S. Army Corps of Engineers have been required to work in wetland areas. To obtain these permits, builders must agree to restore, enhance, or create an equal number

of wetland acres (generally in the same watershed) as those that would be damaged or destroyed in the construction project. Landowners are given the opportunity to balance the adverse effects by replacing environmental values that are lost. This concept is known as wetlands mitigation. Mitigation banking allows developers or public bodies that seek to build on wetlands to make payments to a “bank” for use in the enhancement of other wetlands at a designated location. The development entity purchases “credit” in the bank and transfers full mitigation responsibility to an agency or environmental organization that runs the bank. Environmental professionals design, construct, and maintain a specific natural area using these funds.

The history of the Clean Water Act is much like that of the environmental movement itself. Once widely supported and buoyed by its initial success, the Clean Water Act has encountered increasingly difficult problems, such as polluted stormwater runoff and non-point-source pollution, as well as unforeseen legalistic challenges, such as debate regarding wetlands and property rights. Unfortunately, the Clean Water Act has achieved only part of its goal. At least one-third of the U.S. rivers, one-half of the U.S. estuaries, and more than one-half of the lakes are still not safe for such uses as swimming or fishing. At least 31 states have reported toxins in fish exceeding the action levels set by the Food and Drug Administration (FDA). Every pollutant cited in an USEPA study on chemicals in fish showed up in at least one location. Water quality is seen as deteriorated and viewed as the cause of the decreasing number of shellfish in the waters.

clean Water act facts • The Clean Water Act does not regulate most ditches. • The Clean Water Act does not change exemptions for agriculture. • The Clean Water Act does not regulate erosional features. • The Clean Water Act does not regulate groundwater. • The Clean Water Act does not regulate farm ponds. • The Clean Water Act does not regulate land use. • The Clean Water Act does not change policy on irrigation. • The Clean Water Act does not regulate puddles. • The Clean Water Act does not change policy on stormwater. • The Clean Water Act does not regulate water in tile drains. • The Clean Water Act does not change policy on water transfers.

SAFE DRINKING WATER ACT When we get the opportunity to travel the world, one of the first things we learn to ask is whether or not the water is safe to drink. Unfortunately, in most of the places in the world, the answer is “no.” As much as 80% of all sickness in the world is attributable to inadequate water or sanitation (Masters, 1991). The American ecologist William C. Clark probably summed it up best during a speech in Wisconsin in 1988: “If you could tomorrow morning make water clean in the world, you would have done, in one fell swoop, the best thing you could have done for improving human health by improving environmental quality.” It has been estimated that threefourths of the population in Asia, Africa, and Latin America lack a safe supply of water for drinking, washing, and sanitation (Morrison, 1983). Money, technology, education, and attention to the problem are essential for improving these statistics and to solving the problem that this West African proverb succinctly states: “Filthy water cannot be washed.” Left alone, Nature provides for us. Left alone, Nature feeds us. Left alone, Nature refreshes and sustains us with untainted air. Left alone, Nature provides and cleans the water we need to ingest to survive. As Elliot A. Norse put it, “In every glass of water we drink, some of the water has already passed through fishes, trees, bacteria,

worms in the soil, and many other organisms, including people. . . . Living systems cleanse water and make it fit, among other things, for human consumption” (Hoage, 1985). Left alone, Nature performs at a level of efficiency and perfection we cannot imagine. The problem, of course, is that our human popula-

tions have grown too large to allow Nature to be left alone. Our egos allow us to think that humans are the real reason Nature exists at all. In our eyes, our infinite need for water is why Nature works its hydrologic cycle—to provide the constant supply of drinking water we need to sustain life—but the hydrologic cycle itself is unstoppable, human activity or not. Bangs and Kallen (1985) summed it up best: “Of all our planet’s activities—geological movements, the reproduction and decay of biota, and even the disruptive propensities of certain species (elephants and humans come to mind)—no force is greater than the hydrologic cycle.” Nature, through the hydrologic cycle, provides us with an apparently endless supply of water; however, developing and maintaining an adequate supply of safe drinking water requires the coordinated efforts of scientists, technologists, engineers, planners, water plant operators, and regulatory officials. In this section, we concentrate on the regulations that have been put into place in the United States to protect our water supplies and ensure that they are safe, fresh, and palatable. Legislation to protect drinking water quality in the United States dates back to the Public Health Service Act of 1912. With time, the Act evolved, but not until passage of the Safe Drinking Water Act (SDWA) in 1974 (which has since been amended several times) was federal responsibility extended beyond interstate carriers to include all community water systems serving 15 or more outlets, or 25 or more customers. Prompted by public concern over findings of harmful chemicals in drinking water supplies, the law established the basic federal–state partnership for drinking water that is used today. It focuses on ensuring safe water from public water supplies and on protecting the nation’s aquifers from contamination. Before examining the basic tenets of the SDWA, it is first necessary to define several of the terms used in the Act.

SDWA Definitions* **Action level (AL)**—The amount required to trigger treatment or other action. **Best management practices (BMPs)**—Schedules of activities, prohibitions of practices, maintenance procedures, and other management practices to prevent or reduce the pollution of waters of the United States. **Consumer Confidence Report (CCR) or annual drinking water quality report**—An annual water quality report that a community water system is required to provide to its customers. The CCR helps people make informed choices about the water they drink by letting people know what contaminants, if any, are in their drinking water and how these contaminants may affect their health. The CCR also gives the system a chance to tell customers what it takes to deliver safe drinking water. **Contaminant**—Any physical, chemical, biological, or radiological substance or matter in water. **Discharge of a pollutant**—Any addition of any pollutant to navigable waters from any point source. **Exemption**—A document issued to water systems having technical and financial difficulty meeting the National Primary Drinking Water Regulations; it is effective for 1 year and is granted by the USEPA due to compelling factors. **Likely source**—Where a contaminant could have come from. **Maximum contaminant level (MCL)**—The maximum permissible level of a contaminant in water that is delivered to any user of a public water system. **Maximum contaminant level goal (MCLG)**—The level at which no known or anticipated adverse effects on the health of persons occur and which allows an adequate margin of safety. **Maximum residual disinfectant level (MRDL)**—The highest level of a disinfectant allowed in drinking water. **Maximum residual disinfectant level goal (MRDLG)**—The level of a drinking water disinfectant below which there is no known or expected risk to health. **Microbiological contaminants**—Used as indicators that other, potentially harmful bacteria may be present. **National Pollutant Discharge Elimination System (NPDES)**—The national program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, in addition to imposing and enforcing pretreatment requirements, under Sections 307, 402, 318, and 405 of the Clean Water

Act. Navigable waters—Waters of the United States, including territorial seas. pCi/L—Picocuries per liter (measure of radioactivity). Person—An individual, corporation, partnership, association, state, municipality, commission, or political subdivision of a state or any interstate body. Point source—Any discernible, confined, and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture. Pollutant—Dredged soil, solid waste, incinerator residue, filter backwash, sewage, garbage, sewage sludge, munitions, chemical wastes, biological materials, radioactive materials (except those regulated under the Atomic Energy Act of 1954), heat, wrecked or discarded equipment, rock, sand, cellar dirt, or industrial, municipal, and agricultural waste discharged into water. It does not include: (a) sewage from vessels, or (b) water, gas, or other material that is injected into a well to facilitate production of oil or gas, or water derived in association with oil and gas production and disposed of in a well, if the well used either to facilitate production or for disposal purposes is approved by authority of the state in which the well is located, and if the state determines that the injection or disposal will not result in the degradation of ground or surface water sources. Public water system (PWS)—A system for the provision to the public of piped water for human consumption, if such system has at least 15 service connections or regularly serves at least 25 individuals.

Publicly owned treatment works (POTW)—Any device or system used in the treatment of municipal sewage or industrial wastes of a liquid nature which is owned by a state or municipality; includes sewer, pipes, or other conveyances only if they convey wastewater to a POTW providing treatment. Recharge zone—The area through which water enters a sole or principal source aquifer. Regulated substances—Substances regulated by the USEPA and that cannot be present at levels above the MCL. Significant hazard to public health—Any level of contaminant that causes or may cause the aquifer to exceed any maximum contaminant level set forth in any promulgated National Primary Drinking Water Regulations at any point where the water may be used for drinking purposes or which may otherwise adversely affect the health of persons, or which may require a public water system to install additional treatment to prevent such adverse effect. Sole or principal source aquifer—An aquifer that supplies 50% or more of the drinking water for an area. Streamflow source zone—Upstream headwaters areas that drain into an aquifer recharge zone. Toxic pollutants—Pollutants that after discharge and upon exposure, ingestion, inhalation, or assimilation into any organism will, on the basis of the information available, cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions, or physical deformations in such organisms or their offspring. Treatment technique (TT)—A required process intended to reduce the level of a substance in drinking water. Turbidity—A measure of the cloudiness of water; turbidity is not necessarily harmful but can interfere with the disinfection of drinking water. Unregulated monitored substances—Substances that are not regulated by the USEPA but must be monitored so information about their presence in drinking water can be used to develop limits. Variance—Document issued to water systems having technical and financial difficulty meeting National Primary Drinking Water Regulations; it postpones compliance when such a delay will not result in an unreasonable risk to health. Waters of the United States—(a) All waters that are currently used, were used in the past, or may be susceptible to use in interstate or foreign commerce, including all waters that are subject to the ebb and flow of the tide; (b) all interstate waters, including interstate wetlands; (c) all other waters, such as interstate lakes, rivers, streams, mudflats, sand-

flats, wetlands, sloughs, prairie potholes, wet meadows, playa lakes, or natural ponds, the use, degradation, or destruction of which would affect or could affect interstate or foreign commerce. Wetlands—Areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.

SDWA specific provisions To ensure the safety of public water supplies, the Safe Drinking Water Act requires the USEPA to set safety standards for drinking water. Standards are now in place for over 80 different contaminants. The USEPA sets a maximum level for each contaminant; however, in cases where making this distinction is not economically or technologically feasible, the USEPA specifies an appropriate treatment technology instead. Water suppliers must test their drinking water supplies and maintain records to ensure quality and safety. Most states carry the responsibility for ensuring that their public water supplies are in compliance with the national safety standards. Provisions also authorize the USEPA to conduct basic research on drinking water contamination, to provide technical assistance to states and municipalities, and to provide grants to states to help them manage their drinking water programs. To protect groundwater supplies, the law provides a framework for managing underground injection compliance. As part of that responsibility, the USEPA may disallow new underground injection wells based on concerns over possible contamination of a current or potential drinking water aquifer. Each state is expected to administer and enforce the SDWA regulations for all public water systems. Public water systems must provide water treatment, ensure proper drinking water quality through monitoring, and provide public notification of contamination problems. The 1986 amendments to the SDWA significantly expanded and strengthened its protection of drinking water. Under the 1986 provisions, the SDWA required six basic activities:

1. Establishment and enforcement of maximum contaminant levels (MCLs)— These are the maximum levels of certain contaminants that are allowed in drinking water from public systems. Under the 1986 amendments, the USEPA has set numerical standards or treatment techniques for an expanded number of contaminants.
2. Monitoring—The USEPA requires monitoring of all regulated and certain unregulated contaminants, depending on the number of people served by the system, the source of the water supply, and the contaminants likely to be found.
3. Filtration—The USEPA has criteria for determining which systems are obligated to filter water from surface water sources.
4. Disinfection—The USEPA must develop rules requiring all public water supplies to disinfect their water.
5. Use of lead materials—The use of solder or flux containing more than 0.2% lead or pipes and pipe fittings containing more than 8% lead is prohibited in public water supply systems. Public notification is required where lead is used in construction materials of the public water supply system or where water is sufficiently corrosive to cause leaching of lead from the distribution system or lines.

6. Wellhead protection—All states are required to develop wellhead protection programs designed to protect public water supplies from sources of contamination. The USEPA developed national drinking water regulations to meet the requirements of the SDWA. These regulations are subdivided into National Primary Drinking Water Regulations (40 CFR 141), which specify maximum contaminant levels (MCLs) based on health-related criteria, and the National Secondary Drinking Water Regulations (40 CFR 143), which are unenforceable guidelines based on aesthetic qualities, such as taste, odor, and color of drinking water, as well as on nonaesthetic qualities, such as corrosivity and hardness. In setting MCLs, the USEPA is required to balance the public health benefits of the standard against what is technologically and economically feasible. In this way, MCLs are different from other set standards, such as National Ambient Air Quality Standards (NAAQS), which must be set at levels that protect public health regardless of cost or feasibility (Masters, 1991). Note: If monitoring the contaminant level in drinking water is not economically or technically feasible, the USEPA must specify a treatment technique that will effectively remove the contaminant from the water supply or reduce its concentration. The MCLs currently cover a number of volatile organic chemicals, organic chemicals, inorganic chemicals, and radionuclides, as well as microorganisms and turbidity (cloudiness or muddiness). The MCLs are based on an assumed human consumption of 2 liters (roughly 2 quarts) of water per day. The USEPA also creates unenforceable maximum contaminant level goals (MCLGs), which are set at levels that present no known or anticipated health effects and include a margin of safety, regardless of technological feasibility or cost. The USEPA is also required (under SDWA) to periodically review the actual MCLs to determine whether they can be brought closer to the desired MCLGs. Note: For noncarcinogens, MCLGs are arrived at in a three-step process. The first step is calculating the reference dose (RfD) for each contaminant. The RfD is an estimate of the amount of a chemical that a person can be exposed to on a daily basis that is not anticipated to cause adverse systemic health effects over the person's lifetime. A different assessment system is used for chemicals that are potential carcinogens. If toxicological evidence leads to the classification of the contaminant as a human or probable human carcinogen, the MCLG is set at zero (Boyce, 1997).

National Primary Drinking Water Regulations Categories of primary contaminants include organic chemicals, inorganic chemicals, microorganisms, turbidity, and radionuclides. Except for some microorganisms and nitrates, water that exceeds the listed MCLs will pose no immediate threat to public health; however, all of these substances must be controlled, because drinking water that exceeds the standards over long periods of time may be harmful. Note: As we learn more from research about the health effects of various contaminants, the number of regulated organics is likely to grow. Public drinking water supplies must be sampled and analyzed for organic chemicals at least every 3 years.

Organic Chemicals Organic contaminants for which MCLs are being promulgated are classified into the following three groupings: synthetic organic chemicals (SOCs), volatile organic chemicals (VOCs), and trihalomethanes (THMs). Table 3.1 provides a partial list

of maximum allowable levels for several selected organic contaminants. Synthetic organic chemicals are manmade and are often toxic to living organisms. These compounds are used in the manufacture of a wide variety of agricultural and industrial products. This group includes primarily PCBs, carbon tetrachloride, pesticides and herbicides such as 2,4-D, aldicarb, chlordane, dioxin, xylene, phenols, and thousands

of other synthetic chemicals. Note: As we learn more from research about the health effects of various contaminants, the number of regulated organics is likely to grow. Public drinking water supplies must be sampled and analyzed for organic chemicals at least every 3 years. Note: A study of 29 Midwestern cities and towns by the Washington, DC-based nonprofit Environmental Working Group found pesticide residues in the drinking water in nearly all of them. In Danville, Illinois, the level of cyanazine, a weed killer manufactured by DuPont, was 34 times the federal standard. In Fort Wayne, Indiana, one glass of tap water contained nine kinds of pesticides. The fact is, each year, approximately 2.6 billion pounds of pesticides are used in the United States (Lewis, 1996). These pesticides find their way into water supplies and thus present increased risk to public health. Volatile organic chemicals are synthetic chemicals that readily vaporize at room temperature. Chemicals used in degreasing agents, paint thinners, glues, dyes, and some pesticides fall into this category. VOCs include benzene, carbon tetrachloride, 1,1,1-trichloroethane (TCA), trichloroethylene (TCE), and vinyl chloride. Note: VOCs are particularly dangerous in water. They are absorbed through the skin through contact with water—for example, every shower or bath. Hot water allows these compounds to evaporate rapidly, and they are harmful if inhaled. VOCs can be present in any tap water, regardless of location or water source. If tap water contains significant levels of these compounds, they pose a health threat from skin contact, even if the water is not ingested (Ingram, 1991). Trihalomethanes (THMs) are created in the water itself as byproducts of water chlorination. Chlorine (present in essentially all U.S. tap water) combines with organic chemicals to form THMs (see Figure 3.1). They include chloroform, bromodichloromethane, dibromochloromethane, and bromoform. Note: THMs are known carcinogens—substances that increase the risk of getting cancer—and they are present at varying levels in all public tap water.

Inorganic Chemicals Several inorganic substances (particularly lead, arsenic, mercury, and cadmium) are of public health importance. These inorganic contaminants and others contaminate drinking water supplies as a result of natural processes, environmental factors, or, more commonly, human activity. Some of these are listed in Table 3.2. For most inorganics, MCLs are the same as MCLGs, but the MCLG for lead is zero.

Microorganisms (Microbiological Contaminants) This group of contaminants includes bacteria, viruses, and protozoa, which can cause typhoid, cholera, and hepatitis, as well as other waterborne diseases. Bacteria are closely monitored in water supplies because they can be dangerous and because their presence is easily detected. Because tests designed to detect individual microorganisms in water are difficult to perform, in actual practice a given water supply is not tested by individually testing for specific pathogenic microorganisms. Instead, a simpler technique is used, based on testing water for evidence of any fecal contamination. Coliform bacteria are used as indicator organisms whose presence suggests that the water is contaminated. In testing for total coliforms, the number of monthly samples required is based on the population served and the size of the distribution system. Because the number of coliform bacteria excreted in feces is on the order of 50 million per gram and the concentration of coliforms in untreated domestic wastewater is usually several million per 100 mL, it is highly unlikely that water contaminated with human wastes would have no coliforms. That conclusion is the basis for the drinking water standard for microbiological contaminants, which specifies in essence that, on the average, water should contain no more than 1 coliform per 100 mL. The SDWA standards now require that coliforms not be found in more than 5% of the samples examined during a 1-month period. Known as the presence/absence concept, it replaces

previous MCLs based on the number of coliforms detected in the sample. Viruses are very common in water. If we removed a teaspoonful of water from an unpolluted lake, over 1 billion viruses would be present in the water (Figure 3.2). The two most common and troublesome protozoa found in water are *Giardia* and *Cryptosporidium* (or *Crypto*). In water, these protozoa occur in the form of hardshelled cysts. Their hard covering makes them resistant to chlorination and chlorine residual that kills other organisms. We cover microorganisms commonly found in water in much greater detail in Chapter 6.

Turbidity Turbidity, a measure of fine suspended matter in water, is primarily caused by clay, silt, organic particulates, plankton, and other microscopic organisms, ranging in size from colloidal to coarse dispersion. Turbidity in the water is expressed in nephelometric turbidity units (NTUs), which represent the amount of light scattered or reflected from the water. Turbidity is officially reported in standard units known as Jackson turbidity units, which are equivalent to milligrams per liter of silica (diatomaceous earth) that could cause the same optical effect. Turbidity testing is not required for groundwater sources.

Radionuclides Radioactive contamination of drinking water is a serious matter. Radionuclides (the radioactive metals and minerals that cause this contamination) come from both natural and man-made sources. Naturally occurring radioactive minerals move from underground rock strata and geologic formations into the underground streams flowing through them and primarily affect groundwater. In water, radium-226, radium-228, radon-222, and uranium are the natural radionuclides of most concern. Uranium is typically found in groundwater and, to a lesser degree, in some surface waters. Radium in water is found primarily in groundwater. Radon, a colorless, odorless gas and a known cancer-causing agent, is created by the natural decay of minerals. Radon is an unusual contaminant in water, because the danger arises not from drinking radon-contaminated water but from breathing the gas after it has been released into the air. Radon dissipates rapidly when exposed to air (see Figure 3.3). When present in household water, it evaporates easily into the air, where household members may inhale it. Some experts believe that the effects of radon inhalation are more dangerous than those of any other environmental hazard. Man-made radionuclides (more than 200 are known) are believed to be potential drinking water contaminants. Manmade sources of radioactive minerals in water are nuclear power plants, nuclear weapons facilities, radioactive materials disposal sites, and docks for nuclear-powered ships.

National Secondary Drinking Water Regulations The National Secondary Drinking Water Regulations are non-enforceable guidelines regulating contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. A range of concentrations is established for substances that affect water only aesthetically and have no direct effect on public health. Table 3.3 presents some secondary standards.

amendments to the sDWA After more than 3 years of effort, the Safe Drinking Water Act Reauthorization (one of the most significant pieces of environmental legislation passed to date) was adopted by Congress and signed into law by President Clinton in 1996. The new streamlined version of the original SDWA gave states greater flexibility in identifying and considering

the likelihood for contamination in potable water supplies and in establishing monitoring criteria. It established increased reliance on sound science instead of feel-good science, paired with more consumer information presented in readily understandable form, and it called for increased attention to the assessment and protection of source waters. The significance of the 1996 SDWA amendments lies in the fact that they were a radical rewrite of the law that the USEPA, states, and water systems had been trying to implement

for the previous 10 years. In contrast to the 1986 amendments (which were crafted with little substantive input from the regulated community and embraced a command-and-control approach with compliance costs rooted in water rates), the 1996 amendments were developed with significant contributions from water suppliers and state and local officials and embodied a partnership approach that included major new infusions of federal funds to help water utilities—especially the thousands of smaller systems—comply with the law. Table 3.4 provides a summary of many of the major provisions of the 1996 amendments, which are as complex as they are comprehensive. Additional SDWA amendments have been proposed and passed since 1996.

implementing the sDWA On December 3, 1998, at the oceanfront of Fort Adams State Park, Newport, Rhode Island, President Clinton announced significant updates of the 1996 SDWA amendments, with the expectation that the new requirements would protect most of the nation from dangerous contaminants while adding only about \$2 to many monthly water bills. The rules required approximately 13,000 municipal water suppliers to use better filtering systems to screen out *Cryptosporidium* and other microorganisms, ensuring that U.S. community water supplies would be safe from microbial contamination. In his speech, President Clinton said:

This past summer I announced a new rule requiring utilities across the country to provide their customers regular reports on the quality of their drinking water. When it comes to the water our children drink, Americans cannot be too vigilant. Today I want to announce three other actions I am taking. First, we're escalating our attack on the invisible microbes that sometimes creep into the water supply. . . . Today, the new standards we put in place will significantly reduce the risk from *Cryptosporidium* and other microbes, to ensure that no community ever has to endure an outbreak like the one Milwaukee suffered. Second, we are taking steps to ensure that when we treat our water, we do it as safely as possible. One of the great health advances to the 20th century is the control of typhoid, cholera, and other diseases with disinfectants. Most of the children in this audience have never heard of typhoid and cholera, but their grandparents cowered in fear of it, and their great-grandparents took it as a fact of life that it would take away significant numbers of the young people of their generation. But as with so many advances, there are trade-offs. We now see that some of the disinfectants we use to protect our water can actually combine with natural substances to create harmful compounds. So today I'm announcing standards to significantly reduce our exposure to these harmful byproducts, to give our families greater peace of mind with their water. The third thing we are doing today is to help communities meet higher standards, releasing almost \$800 million to help communities in all 50 states to upgrade their drinking water systems . . . to give 140 million Americans safer drinking water. Consumer Confidence Reports In his comments, President Clinton mentioned the requirement of community water systems to put annual drinking water quality reports into the hands of their customers (see Table 3.4). While water systems are free to enhance their reports in any useful way, each report must provide consumers with the following fundamental information about their drinking water:

- The lake, river, aquifer, or other source of the drinking water. Consider the following actual report provided by a city referred to here as Capital City: Capital City receives its raw (untreated) water from eight reservoirs, two rivers, and four deep wells. From these sources, raw water is pumped to one of the Department of Utilities' two water treatment plants, where it is filtered and disinfected. Once tested for top quality, Capital City drinking water is pumped on demand to your tap.
- A brief summary of the susceptibil-

ity to contamination of the local drinking water source, based on the source water assessments by states. Consider the following actual information provided by Capital City: Contaminants that may be present in source (raw) water include – Microbial contaminants, such as viruses and bacteria, which may come from sewage treatment plants, septic systems, agricultural livestock operations, wildlife – Inorganic contaminants, such as salts and metals, which can be naturally occurring or result from urban stormwater runoff, industrial or domestic; wastewater discharges; oil and gas production; mining; or farming – Pesticides and herbicides, which may come from a variety of sources such as agriculture, urban stormwater runoff, and residential uses – Radioactive contaminants, which can be naturally occurring or the result of oil and gas production and mining activities • How to get a copy of the water system’s complete source water assessment. Consider the following taken from Capital City’s Consumer Confidence Report (annual drinking water quality report): For a copy of the water system’s complete source water assessment and questions regarding this report contact Capital City’s Water Quality Lab at xxx-xxx-xxxx. For more information about decisions affecting your drinking water quality, you may attend Capital City city council meetings. For times and agendas, call Capital City Clerk’s Office at xxx-xxx.xxxx. • The level (or range of levels) of any contaminant found in local drinking water, as well as USEPA’s health-based standard (maximum contaminant level) for comparison.

The likely source of that contaminant in the local drinking water supply. • The potential health effects of any contaminant detected in violation of an USEPA health standard and an accounting of the system’s actions to restore safe drinking water. • The water system’s compliance with other drinking water-related rules. • An educational statement for vulnerable populations about avoiding *Cryptosporidium*. • Educational information on nitrate, arsenic, or lead in areas where these contaminants may be a concern. With regard to the levels of contaminants, their possible sources, and the levels detected in local drinking water supplies, consider the information provided by Capital City to its ratepayers in the city’s annual drinking water quality report for 2011, which is shown in Table 3.5. • Phone numbers of additional sources of information, including the water system and USEPA’s Safe Drinking Water Hotline (800-426-4791).

This information supplements public notification that water systems must provide to their customers upon discovering any violation of a contaminant standard. This annual report should not be the primary notification of potential health risks posed by drinking water; rather, it provides customers with water quality information from the previous year.

Drinking Water Supplies INTRODUCTION Where do we get our drinking water from? What is the source?

The answer would most likely turn to one of two possibilities: groundwater or surface water. This answer seems simple enough, because these two sources are, indeed, the primary sources of most water supplies. From the earlier discussion about the hydrologic or water cycle, we know that, from whichever source we obtain our drinking water, the source is constantly being replenished (we hope) with a supply of freshwater. This water cycle phenomenon was best summed up by Heraclitus of Ephesus, who said, “You could not step twice into the same river; for other waters are ever flowing on to you.” This chapter discusses one of the drinking water practitioner’s primary duties—finding and securing a source of potable water for human use.

WATER SOURCES* In the real estate business, location is everything. The same can be said when it comes to sources of water. In fact, the presence of water defines “location” for communities. Although communities differ widely in character and size, all have the common concerns of finding water for indus-

trial, commercial, and residential use. Freshwater sources that can provide stable and plentiful supplies for a community do not always occur where we wish. Simply put, on land, the availability of a regular supply of

potable water is the most important factor affecting the presence—or absence—of many life forms. A map of the world immediately shows us that surface waters are not uniformly distributed over the surface of the Earth. American lands hold rivers, lakes, and streams on only about 4% of their surface. The heaviest populations of any life forms, including humans, are found in regions of the United States (and the rest of the world) where potable water is readily available, because lands barren of water simply cannot support large populations. Note: The volume of freshwater sources depends on geographic, landscape, and temporal variations, as well as on the impact of human activities.

Just how readily available is potable Water? Approximately 326 million cubic miles of water comprise Earth's entire water supply. Although it provides us indirectly with freshwater through evaporation from the oceans, only about 3% of this massive amount of water is fresh, and most of that minute percentage of freshwater is locked up in polar ice caps and glaciers. The rest is held in lakes, in flows through soil, and in river and stream systems. Only 0.027% of Earth's freshwater is available for human consumption (see Table 4.1 for the

distribution percentages of Earth's water supply). We see from Table 4.1 that the major sources of drinking water are from surface water, groundwater, and from groundwater under the direct influence of surface water (i.e., springs or shallow wells).

surface Water supplies Most surface water originates directly from precipitation—rainfall or snow. To gain an appreciation for the impact of this runoff on surface water supplies, let's take a look at the water balance in the United States. Over the U.S. mainland, rainfall averages about 4250 billion gallons per day.

Of this massive amount, about 66% returns to the atmosphere through evaporation directly from the surface of lakes and rivers and transpiration from plants. This leaves about 1250 billion gallons per day to flow across or through the ground to return to the sea (see Table 4.2). Although municipal usage of water is only a small fraction of this great volume, the per capita consumption of water in the United States is rather high—about 80 to 100 gallons per person per day (USGS, 2016), probably because public water is relatively inexpensive here. In areas where water supplies are less readily available and thus more costly, per capita consumption is much lower, due to both financial and conservation concerns.

The 1250 billion gallons per day of surface runoff water, exposed and open to the atmosphere, results from the movement of water on and just beneath the surface of the Earth, referred to as overland flow. Simply put, overland flow and surface runoff are the same—water flow that has not yet reached a definite stream channel. This occurs when the rate of precipitation exceeds either the rate of interception and evapotranspiration or the amount of rainfall readily absorbed by the surface of the Earth. The total land area that contributes runoff to a stream or river is called a watershed, drainage basin, or catchment area. Specific sources of surface water include

- Rivers • Streams • Lakes • Impoundments (manmade lakes made by damming a river or stream) • Very shallow wells that receive input via precipitation • Springs affected by precipitation (flow or quantity directly dependent upon precipitation) • Rain catchments (drainage basins) • Tundra ponds or muskegs (peat bogs)

Surface water has advantages as a source of potable water. Surface water sources are usually easy to lo-

cate; unlike groundwater, finding surface water does not require a geologist or hydrologist. Normally, surface water is not tainted with minerals precipitated from the Earth's strata. Ease of discovery aside, surface water also presents some disadvantages. Surface water sources are easily contaminated with microorganisms that can cause waterborne diseases and are polluted by chemicals that enter from surrounding runoff and upstream discharges. Water rights can also present problems. As we have said, most surface water is the result of surface runoff. The amount and flow rate of this surface water are highly variable for two main reasons: (1) human interference, and (2) natural conditions. In some cases, surface water quickly runs off land surfaces. From a water resources standpoint, this is generally undesirable, because quick runoff does not provide enough time for the water to infiltrate into the ground and recharge groundwater aquifers. Also, surface water that quickly runs off land causes erosion and flooding problems. Probably the only good thing that can be said about surface water that runs off quickly is that it usually does not have enough contact time to increase in mineral content. Surface water that drains slowly off land has all the opposite effects. Drainage basins collect surface water and direct it on its gravitationally influenced path to the ocean. The drainage basin is normally characterized as an area measured in square miles, acres, or sections. Obviously, if a community is drawing water from a surface water source, the size of its drainage basin is an important consideration. Surface water runoff, like the flow of electricity, flows or follows the path of least resistance. Surface water within the drainage basin normally flows toward one primary watercourse (e.g., river, stream, brook, creek), unless some manmade distribution system (canal or pipeline) diverts the flow. Surface water runoff from land surfaces depends on several factors (see Figure 4.1):

- Rainfall duration—Even a light, gentle rain, if it lasts long enough, can, with time, saturate soil and allow runoff to take place.
- Rainfall intensity—With increases in intensity, the surface of the soil quickly becomes saturated. This saturated soil can hold no more water; as more rain falls and water builds up on the surface, surface runoff is produced.
- Soil composition—The composition of the surface soil directly affects the amount of runoff; for example, it is obvious that hard rock surfaces result in 100% runoff. Clay soils have very small void spaces that swell when wet; when these void spaces fill and close, they do not allow infiltration. Coarse sand possesses large void spaces that allow water to flow easily through it, thus producing the opposite effect of clay soil, even in a torrential downpour.
- Soil moisture—The amount of existing moisture in the soil has a definite impact on surface water runoff. Soil already wet or saturated from a previous rain causes surface water runoff to occur sooner than if the soil were dry. Surface water runoff from frozen soil can be as high as 100% of the snow melt or rain runoff because frozen ground is basically impervious.
- Vegetation cover—Groundcover limits runoff. Roots of vegetation and pine needles, pine cones, leaves, and branches create a porous layer (a sheet of decaying natural organic substances) above the soil. This porous, organic layer readily allows water into the soil. Vegetation and organic waste also act as cover to protect the soil from hard, driving rains, which can compact bare soils, close off void spaces, and increase runoff. Vegetation and groundcover work to maintain the infiltration and water-holding capacity of the soil and also work to reduce soil moisture evaporation.
- Ground slope—When rain falls on steeply sloping ground, 80% or more may become surface runoff. Gravity moves the water down the surface more quickly than it can infiltrate the surface. Water flow off flat land is usually slow enough to provide opportunity for a higher percentage of the rainwater to infiltrate the ground.
- Human influences—Various human activities have a definite impact on surface water runoff. Most human activities tend to increase the rate of water flow; for example, canals and ditches are usually constructed

to provide

steady flow, and agricultural activities generally remove groundcover that would work to retard the runoff rate. At the opposite extreme, manmade dams are generally built to retard the flow of runoff.

groundwater supply Unbeknownst to many of us, our Earth possesses an unseen ocean. This ocean, unlike the surface oceans that cover most of the globe, is freshwater: the groundwater that lies contained in aquifers beneath Earth's crust. This gigantic water source forms a reservoir that feeds all the natural fountains and springs of this planet, but how does water travel into the aquifers that lie under the surface of the Earth? Groundwater sources are replenished from a percentage of the average approximately 3 feet of water that falls to Earth each year on every square foot of land. Water falling to Earth as precipitation follows three courses. Some runs off directly to rivers and streams (roughly 6 inches of that 3 feet), eventually working its way back to the sea. Evaporation and transpiration through vegetation takes up about 2 feet. The remaining 6 inches seeps into the ground, entering and filling every interstice, each hollow and cavity. Although groundwater accounts for only 1/6 of the total 1,680,000 miles of water, if we could spread this water out over the land, it would blanket it to a depth of 1000 feet. Almost all groundwater is in constant motion through the pores and crevices of the aquifer in which it occurs. The water table is rarely level; it generally follows the shape of the ground surface. Groundwater flows in the downhill direction of the sloping water table. The water table sometimes intersects low points of the ground, where it seeps out into springs, lakes, or streams. Usual groundwater sources include wells and springs that are not influenced by surface water or local hydrologic events. As a potable water source, groundwater has several advantages over surface water. Unlike surface water, groundwater is not easily contaminated. Groundwater sources are usually lower in bacteriological contamination than surface waters. Groundwater quality and quantity usually remain stable throughout the year. In the United States, groundwater is available in most locations. As a potable water source, groundwater does present some disadvantages compared to surface water sources. Operating costs are usually higher, because groundwater supplies must be pumped to the surface. Any contamination is often hidden

from view, and removing contaminants can be very difficult. Groundwater often possesses high mineral levels and thus an increased level of hardness, because it is in contact longer with minerals. Near coastal areas, groundwater sources may be subject to saltwater intrusion. Note: Groundwater quality is influenced by the quality of its source. Changes in source waters or degraded quality of source supplies may seriously impair the quality of the groundwater supply.

SUMMARY Our freshwater supplies are constantly renewed through the hydrologic cycle, but the normal ratio of freshwater to saltwater is not subject to change. As our population grows and we move into lands without ready freshwater supplies, we place ecological strain upon those areas and on their ability to support life. Communities that build in areas without adequate local water supplies are putting themselves at risk. Proper attention to our surface and groundwater sources, including remediation, pollution control, and water reclamation and reuse, can help to ease the strain, but technology cannot fully replace adequate local freshwater supplies, whether from surface water or groundwater sources. Drinking Water Conveyance and Distribution

INTRODUCTION Before beginning our discussion of drinking water conveyance and distribution systems, let's review the information covered to this point. In many cases, a municipal water supply provides drinking water for use in homes and industries. This same water supply source may also be used for

irrigation, for extinguishing fires, for street cleaning, for carrying wastes to treatment facilities, and for many other purposes. The two most important factors in any water supply are its quantity and quality (Q and Q factors). We now need to add a third factor to the mix: the location of the water supply relative to points of use. Note that each type of water use has its own prerequisites. Food processing plants, for example, require large volumes and high water quality. Waste conveyance systems, on the other hand, require only quantity or volume. Recall that the earliest communities were almost exclusively located near a water source (see Figure 5.1). Further, the evolution of public water supply systems is tied directly to the growth of cities. In cases where a surface water source was not available, settlers dug wells to supply water to community residents.

A typical water supply system consists of six functional elements: (1) a source or sources of supply; (2) storage facilities (e.g., impoundment reservoirs); (3) transmission facilities to transport water from the point of storage to the treatment plant; (4) treatment facilities for altering water quality; (5) transmission and storage facilities for transporting water to intermediate points (such as water towers or standpipes); and (6) distribution facilities for bringing water to individual users (see Figure 5.2). Recall that when precipitation falls on a watershed or catchment area, it either flows as runoff above ground to streams and rivers or soaks into the ground to reappear in springs or where it can be drawn from wells. A water supply can come from a catchment area that may contain several thousands of acres (or hectares) of land, draining to streams whose flow is retained in impoundment reservoirs. If a water supply is drawn from a large river or lake, the catchment area is the entire area upstream from the point of intake. Obviously, the amount of water that enters a water supply system depends on the amount of precipitation and the volume of the runoff. The annual average precipitation in the United States is about 30 inches, of which two-thirds is lost to the atmosphere by evaporation and transpiration. The remaining water becomes runoff into rivers and lakes or, through infiltration, replenishes groundwater. Precipitation and runoff vary greatly with geography and season. Drinking water comes from surface water and groundwater. Large-scale water supply systems tend to rely on surface water resources; smaller water systems tend to use groundwater. If surface water is the source of supply for a particular drinking water supply system, the water is obtained from lakes, streams, rivers, or ponds. Storage reservoirs (artificial lakes created by constructing dams across stream valleys) can hold back higher than average flows and release them when greater flows are needed. Water supplies may be taken directly from reservoirs or from locations downstream of the dams. Reservoirs may serve other purposes in addition to water supply, including flood mitigation, hydroelectric power, and water-based recreation. Groundwater is pumped from natural springs, from wells, and from infiltration galleries, basins, or cribs. Most small and some large U.S. water systems use groundwater as their source of supply. Groundwater may be drawn from the pores of alluvial, glacial, or aeolian deposits of granular unconsolidated material (such as sand and gravel); from the solution passages, caverns, and cleavage planes of sedimentary rocks (such as limestone, slate, and shale); and from combinations of these geologic formations. Groundwater sources may have intake or recharge areas that are miles away from points of withdrawal (water-bearing stratum or aquifer). Water quality in aquifers (geologic formations that contain water) and water produced by wells depend on the nature of the rock, sand, or soil in the aquifer from which the well withdraws water. Drinking water wells may be shallow (50 feet or less) or deep (more than 1000 feet). Including the approximately 23 million Americans who use groundwater as private drinking water sources, slightly more than half of the U.S. population receives its

drinking water from groundwater sources. As the title of this chapter indicates, the sections that follow focus on the conveyance and distribution of drinking water. For the purposes of simplifying the discussion about this stage of potable water systems and treatment, the treatment process that most surface water undergoes before it is conveyed and distributed to the consumer will be covered later in Chapter 10.

SURFACE WATER AND GROUNDWATER DISTRIBUTION SYSTEMS Major water supply systems can generally be divided into two categories based on the source of water they use. The water source, in turn, impacts the design, construction, and operation of the water distribution systems. The types of systems, classified by source (see Figures 5.3 and 5.4), are

- Surface water supply systems
- Groundwater supply systems

Surface water (acquired from rivers, lakes, or reservoirs) flows through an intake structure into the transmission system (Figure 5.3). From a groundwater source, flow moves through an intake pipe and then is pumped through a transmission conduit that conveys the water to a distribution system (Figure 5.4). Groundwater is generally available in most of the United States; however, the amount available for withdrawal at any particular location is usually limited. Surface water and groundwater supply systems may be comprised of canals, pipes, and other conveyances; pumping plants; distribution reservoirs or tanks to assist in balancing supplies and demands for water and to control pressures; other appurtenances; and treatment works. Note: To illustrate the process of drinking water supply conveyance and distribution in its most basic form, we concentrate here on the major components of a typical surface water supply and distribution system. In a typical community water supply system, water is transported under pressure through a distribution network of buried pipes. Smaller pipes (house service lines) attached to the main water lines bring water from the distribution network to households. In many community water supply systems, pumping water up into storage tanks that store water at higher elevations than the households they serve provides water pressure. The force of gravity then pushes the water into homes when household taps open. Households on private supplies usually get their water from private wells. A pump brings the water out of the ground and into a small tank within the home, where the water is stored under pressure. In cities, the distribution system generally follows street patterns, but it is also affected by topography and by the types of residential, commercial, and industrial development, as well as the location of treatment facilities and storage works. A distribution system is often divided into zones that correspond to different ground elevations and service pressures. The water pipes (mains) are generally enclosed loops, so supply to any point can be provided from at least two directions. Street mains usually have a minimum diameter of 6 to 8 inches to provide adequate flows for buildings and for fighting fires. The pipes connected to buildings may range down in size to as little as 1 inch for small residences.

surface Water intake Withdrawing water from a lake, reservoir, or river requires an intake structure. Because surface sources of water are subject to wide variations in flow, quality, and temperature, intake structures must be designed so the required flow can be withdrawn despite these natural fluctuations. Surface water intakes consist of screened openings and conduit that conveys the flow to a sump from which it may be pumped to the treatment works. Typical intakes are towers, submerged ports, and shoreline structures. Intakes function primarily to supply the highest quality water from the source and to protect downstream piping, equipment, and unit processes from damage or clogging as a result of floating and submerged debris, flooding, and wave action. To facilitate this, intakes should be located to consider the effects of anticipated variations in water level, navigation requirements, local currents and patterns of sediment de-

position and scour, spatial and temporal variations in water quality, and the quantity of floating debris. For lakes and impounding reservoirs where fluctuating water levels and variations in water quality with depth are common, intake structures that permit withdrawal over a wide range of elevations are typically used. Towers (Figure 5.5) are commonly used for reservoirs and lakes. A tower water intake provides ports located at several depths, avoiding the problems of water quality that stem from locating a single inlet at the bottom, as water quality varies with both time and depth. With the exception of brief periods in spring and fall when overturns may occur, water quality is usually best close to the surface, thus intake ports located at several depths permit selection of the most desirable water quality in any season of the year (see Figure 5.5). Submerged ports also have the advantage of remaining free from ice and floating debris. Selection of port levels must be related to characteristics of the water body (Hammer and Hammer, 1996). Considerations that affect lake intake location include (McGhee, 1991):

- Locate intakes as far as possible from any source of pollution.
 - Factor in wind and current effects on the motion of contaminants.
- Provide sufficient water depth (typically 20 to 30 feet) to prevent blocking of the intake by ice jams that may fill shallower lake areas to the bottom.

River intakes are typically designed to withdraw water from slightly below the surface to avoid both sediment in suspension at lower levels and floating debris; if necessary, they are also located at levels low enough to meet navigation requirements. Generally, river intakes are submerged (see Figure 5.6) or screened shore intakes (see Figure 5.7). Because of low costs, the submerged type is widely used for small river and lake intakes.

Note: Submerged intakes are not readily accessible when they require repair or maintenance. When they are used in lakes or reservoirs, another distinct disadvantage is the lack of alternative withdrawal levels available to provide the highest quality of water throughout the year.

types of surface Water Distribution Along with providing potable water to the household tap, water distribution systems are ordinarily designed to adequately satisfy the water requirements for a combination of domestic, commercial, industrial, and firefighting purposes. The system should be capable of meeting the demands placed on it at all times and at satisfactory pressures. Pipe systems, pumping stations, storage facilities, fire hydrants, house service connections, meters, and other appurtenances are the main elements of the system (Cesario, 1995). Water is normally distributed by one of three different means: gravity distribution, pumping without storage, or pumping with storage. Gravity distribution is possible only when the source of supply is located substantially above the level of the community. Pumping without storage (the least desirable method because it provides no reserve flow and pressures fluctuate substantially) use sophisticated control systems to match an unpredictable demand. Pumping with storage is the most common method of distribution (McGhee, 1991).

Distribution line netWork Distribution systems may be generally classified as grid systems, branching systems, a combination of these, or dead-end systems (see Figure 5.8). The branching system shown in Figure 5.8A is not the preferred distribution network, because it does not furnish supply to any point from at least two directions and because it includes several terminals or dead ends. Normally, grid systems (see Figure 5.8B,C) are the best arrangement for distributing water. All of the arterials and secondary mains are looped and interconnected, eliminating dead ends and permitting water circulation in such a way that a heavy discharge from one main allows drawing water from other pipes. Newly constructed distribution systems avoid the antiquated dead-end system (see Figure 5.8D), and such systems are often retrofitted

later by incorporating proper looping.

service connection to household tap A typical service connection consists of a pipe from the distribution system to a turnoff valve located near the property line (see Figure 5.9).

Distribution and storage Distribution reservoirs and other storage facilities or vessels are in place to provide a sufficient amount of water to average or equalize daily demands on the water supply system (see Figure 5.10). Storage also serves to increase operating convenience, to level out pumping requirements, to decrease power costs, to provide water during power source or pump failure, to provide large quantities of water to meet fire demands, to provide surge relief, to increase detention time, and to blend water sources. Generally, six different types of storage are employed in storing potable water: clear wells, elevated tanks, stand pipes, ground-level reservoirs, hydropneumatic or pressure tanks, and surge tanks.

1. Clear wells are used to store filtered water from a treatment works and serve as chlorine contact tanks (Figure 5.11).
2. Elevated tanks are located above the service zone and are used primarily to maintain an adequate and fairly uniform pressure to the service zone (Figure 5.12).
3. Stand pipes are tanks that stand on the ground; they have a height greater than their diameter (Figure 5.13).
4. Ground-level reservoirs are located above service areas to maintain the required pressures (Figure 5.14).

FIGURE 5.14 Ground-level reservoir.

1. Hydropneumatic or pressure tanks are generally used in small water systems, usually with a well or booster pump. The tank is used to maintain water pressures in the system and to control the operation of the well pump or booster pump (Figure 5.15).
2. Surge tanks are not necessarily storage facilities but are primarily used to control water hammer or to regulate water flow (Figure 5.16). Protective Coatings and Cathodic Protection Storing water in a storage tank that is not properly protected and preserved from corrosion makes little sense and can be highly dangerous. Tanks in improper physical condition actually degrade the water stored within them. With any storage tank, any coating or preservative that will be in contact with potable water must meet the National Sanitation Foundation (NSF) Standard 61. NSF Standard 61 lists the following types of coatings normally used in protecting tank surfaces:

- Epoxy-based coatings • Powdered epoxy coatings • Vitreous coatings such as glass fused to steel • Cement coatings • Polyurethane • Polymer-modified asphaltic membrane • Galvanized steel • Lubricants • Asphaltic coatings • Vinyl ester

The following actions or conditions can enhance the life of coating systems:

- Proper surface preparation prior to coating application • High quality of the coating (paint) • Skilled workmanship • Drying and aging of the coating • Proper maintenance through periodic inspection; spot, partial, or complete removal of old paint; and repainting as necessary

Cathodic protection (an electrical system) is often used in preserving the integrity and material condition of potable water storage tanks by preventing the corrosion and pitting of steel and iron surfaces in contact with water. By passing a low-voltage current through a liquid or soil in contact with the metal in such a manner that the external electromotive force renders that metal structure cathodic, corrosion is transferred to auxiliary sacrificial anodic parts. Intended to corrode rather than the water storage facility corroding, sacrificial anodes are typically made of magnesium or zinc and must be replaced periodically as they are used up. Typically, the anodes are suspended from the tank roof in warm climates or are submerged in cold climates. The life of the sacrificial anode is about 10 years. Note that cathodic protection is not a substitute for the use of a proper interior coating system.

Water Quality Monitoring at Storage Facilities Water stored in potable water storage facilities must be routinely and properly monitored. Monitoring includes determining chlorine residual levels, turbidity, color, coliform analysis, decimal dilution, most probable number (MPN) analysis, and taste and odor analysis.

Water Quality Problems in Storage/Distribution Systems The potable water practitioner may be called upon to troubleshoot water quality problems while water is in storage facilities and distribution systems. Typical water quality problems that might be encountered include taste and odor, turbidity, color, and presence of coliforms; see Table 5.1 for the types of problems commonly encountered, their possible causes, and potential solutions.

Inspection of Storage Facilities Drinking water practitioners must incorporate an annual inspection protocol for storage facilities, to verify the physical condition of the tank and to verify that the tank is maintained in sanitary condition. Recommended items to be inspected include the following:

1. Tank lot • Verify that access to tank location is locked, if possible. • Verify condition of fence. • Verify that surface water is diverted around tank. • Verify that there is no problem with erosion around the tank foundation, drain, and overflow. • Verify condition of the tank lot upkeep.
2. Water quality protection • Exterior and interior steel/concrete are watertight. • Vent is shielded and screened against animals and rain. • Drain is protected and screened to prevent access by animals and surface water. • Overflow is protected and screened to prevent access by animals and surface water. • Roof hatch is watertight. • Sidewall access is watertight. • Accesses are locked and/or bolted. • All other tank openings are curbed, sleeved, and covered to prevent access by animals, surface water, or rain.
3. Tank operational controls • Tank level indicator is operable and accurate. • Water level controls, such as altitude valve and other valves, are working properly. • Telemetry system are operational. • Tank water level recorder is operational.
4. Coating systems and corrosion control (interior and exterior) • Inspect and note cracks and peeling of coating systems. • Inspect and note location of rust on metal tanks. • Inspect and note pits in tank metal. • Inspect and note condition of cathodic protection system. Note: A detailed inspection of the coating system should be performed by qualified persons in accordance with American Water Works Association (AWWA) Standard D101-53. The annual inspection helps to determine when a detailed inspection of the coating system is needed.

SUMMARY Whether a community water supply is taken from surface or groundwater sources, individual community member needs are similar, whether household or industrial. Consumers need consumable water, wash water, irrigation water, and waste conveyance water. Consumers may give little thought to how water arrives at their tap, but the systems described in this chapter provide potable water to these consumers—an essential and valuable service, as anyone who has had to transport potable water during an emergency will tell you. Drinking water distribution and conveyance are only half the job. The other half of the job—making sure the water these systems provide is safe—is a matter of biology (Chapter 6) and disinfection (Chapter 10).

Microbiological Drinking Water Parameters

INTRODUCTION Drinking water practitioners are concerned with water supply and water purification through a treatment process. In treating water, the primary concern, of course, is producing potable water that is safe to drink (free of pathogens) and has no accompanying offensive characteristics, such as a foul taste or odor. To accomplish this, drinking water practitioners must possess a wide-ranging reservoir of knowledge. They quickly learn that water by its very nature is often very dirty. Microorganisms such as bacteria, algae, fungi, and viruses—often 100 million per milliliter—can live in water that is hot or cold, clear or muddy, rapidly flowing or stagnant (Chapelle, 1997). Consequently, to correctly examine raw water for pathogenic microorganisms and to determine the type of treatment necessary to ensure that the quality of the end product—potable water—meets regulatory standards, in addition to accomplishing all the other myriad requirements involved in drinking water processing, the drinking water practitioner must be a combination specialist/generalist. The next three chapters concentrate on the microbiological parameters (this chapter), physical parameters (Chapter 7), and chemical parameters (Chapter 8) that drinking water practitioners must know. As a generalist, the water practitioner requires a great deal of knowledge and skill to understand the “big picture,” so to speak. At the same time, drinking water practitioners must fine-tune their ability to focus on a single target within a broad field. A practitioner whose narrowly focused specialty is not water microbiology must at least have enough knowledge in biological science to enable full comprehension of the fundamental factors concerning microorganisms and their relationships to one another, their effect on the treatment process, and their impact on the environment, human beings, and other organisms. The drinking water practitioner as a generalist must understand the importance of microbiological parameters and what they indicate—the potential of waterborne disease. Microbiological contaminants are associated with undesirable tastes and odors and are considered generators of treatment problems in drinking water technology (algae and fungi, for example), and they are important enough to the practitioner that knowledge of them is essential. This chapter provides fundamental knowledge of water biology for the water practitioner (primarily for the generalist).

MICROBIOLOGY: WHAT IS IT? Biology is generally defined as the study of living organisms (i.e., the study of life). Microbiology is a branch of biology that deals with the study of microorganisms so small in size that they must be studied under a microscope. Microorganisms of interest to the water and wastewater operator include bacteria, protozoa, viruses, and algae, among others.

classification of organisms For centuries, scientists classified the forms of life visible to the naked eye as either animal or plant. Much of the current knowledge about living things was organized by the Swedish naturalist Carolus Linnaeus in 1735. The importance of classifying organisms cannot be overstated, for without a classification scheme establishing criteria for identifying organisms and arranging similar or-

ganisms into groups would be difficult. Probably the most important reason for classifying organisms is to make things less confusing (Wistreich and Lechtman, 1980). Linnaeus was innovative in the classification of organisms. One of his innovations still with us today is the binomial system of nomenclature. Under the binomial system, all organisms are generally described by a two-word scientific name: genus and species. Genus and species are groups that are part of a hierarchy of groups of increasing size, based on their nomenclature (taxonomy): Kingdom Phylum Class Order Family Genus Species

Using this hierarchy and Linnaeus' binomial system of nomenclature, the scientific name of any organism indicates both the genus and the species. The genus name is always capitalized, and the species name begins with a lowercase letter. On occasion, when little chance for confusion exists, the genus name is abbreviated with a single capital letter. The names are always in Latin, so they are usually printed in italics or underlined. Microbe names of interest to the drinking water practitioner include the following: • *Salmonella typhi*, the typhoid bacillus • *Escherichia coli*, a coliform bacteria • *Giardia lamblia*, a protozoa *Escherichia coli* is commonly known as simply *E. coli*, and *Giardia lamblia* is usually referred to by only its genus name, *Giardia*. The water sciences use a simplified system of microorganism classification that is broken down into the kingdoms of animal, plant, and protista. As a general rule, the animal and plant kingdoms contain all of the multicell organisms, and the protists contain all of the single-cell organisms. Along with microorganism classifications based on the animal, plant, and protist kingdoms, microorganisms can be further classified as being eucaryotic or procaryotic (see Table 6.1). A eucaryotic organism is characterized by a cellular organization that includes a well-defined nuclear membrane. A procaryotic organism is characterized by a nucleus that lacks a limiting membrane. To provide the fundamental knowledge of microbiology that drinking water practitioners require, this chapter takes a basic but far-reaching, structured approach. Included is a lengthy and informative discussion of waterborne protozoa such as *Giardia*, *Cryptosporidium*, and others, all of which have received recent media attention.

WATERBORNE DISEASE Average citizens living in the United States or Europe have heard of waterborne disease-causing microorganisms, but in this modern age most people don't give them a second thought, even though the World Health Organization (WHO) estimates that waterborne diseases account for 5 million deaths annually, worldwide. Travelers to various areas of the world often become more familiar with waterborne diseases or illness-causing microorganisms than they would prefer. Consider, for example, the traveler who drinks water here and there and experiences what 17th-century visitors to Paris experienced after drinking the local water. Martin Lister warned that the local water in Paris during that time caused a certain "looseness, and sometimes dysenteries." Quite a few travelers have heard various euphemisms for their upset stomachs, ranging from "Montezuma's revenge" to "Delhi belly." These people have learned to appreciate the value of clean and safe drinking water. All the news about waterborne disease is not necessarily grim, however. Modern sanitation practices have made contracting most of the waterborne diseases (see Table 6.2) rare in the United States

and Europe. It would be foolhardy and deadly for us to forget, however, that in other areas of the world disease-causing organisms are still in the environment—especially that part of the environment that is water (Spellman, 1997). The bottom line is that waterborne diseases have not been eliminated by treatment or even by modern, much improved sanitary conditions, not even in the industrialized parts of the world. When we refer to waterborne disease, the uninitiated may get the wrong impression about water and waterborne disease. In the water environment, water is not a medium for the growth of pathogenic

microorganisms, but instead is a means of transmission or conveyance (a conduit—hence, use of the term waterborne) of the pathogen to the place where an individual inadvertently consumes it, and thus the outbreak of disease begins (Koren, 1991). The facts are summed up simply enough by the following (Spellman, 1997): Waterborne pathogens are not at home in water. Nothing could be further from the truth. A water-filled environment is not one in which pathogenic organisms would choose to live—that is, if it had such a choice. The point is that microorganisms do not normally grow, reproduce, and thrive in watery surroundings. Pathogenic microorganisms temporarily residing in water are simply biding their time, going with the flow, waiting for their opportunity to meet up with their unsuspecting host or hosts. To some degree, when the pathogenic microorganism finds a host, it is finally home and may have found its final resting place.

BACTERIA* Of all the microorganisms studied in this text, bacteria are the most widely distributed, the smallest in size, the simplest in morphology (structure), and the most difficult to identify and classify. Because of considerable diversity, even providing a descriptive definition of a bacterial organism is difficult. About the only generalization that can be made is that bacteria are single-celled plants, are procaryotic (the nucleus lacks a limiting membrane), are seldom photosynthetic, and reproduce by binary fission. Bacteria are found everywhere in our environment—they are present in the soil, in the air, and in the water. Bacteria are also present in and on the bodies of all living creatures, including humans. Most bacteria do not cause disease; not all of them are pathogenic. Many bacteria perform useful and necessary functions related to the life of larger organisms. cause; in fact, “the form of water pollution that poses the most direct menace to human health is bacteriological contamination” (Black-Covilli, 1992). This is partly the reason why bacteria are of great importance to water specialists. For water treatment personnel tasked with providing the public with safe, portable water, controlling and eliminating disease-causing bacteria pose a constant challenge (see Table 6.3). Attempts to eliminate disease have placed bacteria high on the list of microorganisms of great interest to the scientific community. This interest has spawned much work geared toward enhancing our understanding of bacteria; however, we still have a great deal to learn about bacteria. We are still principally engaged in making observations and collecting facts, trying wherever possible to relate one set of facts to another but still lacking much of a basis for grand unifying theories. One of the important aspects of bacteria for which we still lack complete understanding is the infecting dose. Determining, for example, the number of viable pathogenic cells necessary to produce infections is difficult. The National Academy of Sciences (NAS, 1977, 1982), for example, reported values varying from 103 to 109 pathogenic cells per person, with subjects infected representing from 1 to 95% of the total subjects tested. Other factors such as age and general health, as well as previous exposure, are important. Additional significant influencing factors include the survival of an organism in water, water temperature, and the presence of colloidal matter in water.

bacterial cells: shapes, forms, sizes, and arrangements Since the 19th century, scientists have known that all living things, whether animal or plant, are made up of cells. The fundamental unit of all living matter, no matter how complex, is the cell. A typical cell is a single entity, isolated from other cells by a membrane or cell wall. The cell membrane contains protoplasm, the living material found within it, and the nucleus. In a typical mature plant cell, the cell wall is rigid and is composed of nonliving material, whereas in the typical animal cell the wall is an elastic living membrane. Cells exist in a very great variety of sizes and shapes, and their functions also vary widely. The sizes of cells range from bacteria too small to be

seen with a light microscope to the largest known single cell, the ostrich egg. Microbial cells also have an extensive size range, some being larger than human cells (Kordon, 1993). Bacteria come in three shapes: elongated rods called bacilli, rounded or spherical cells called cocci, and spirals (helical and curved) called spirilla (rigid cell wall) or spirochetes (flexible cell wall). Elongated rod-shaped bacteria may vary considerably in length; they may have square, round, or pointed ends and may be either motile or nonmotile. The spherical-shaped bacteria may occur singly, in pairs, in tetrads, in chains, or in irregular masses. The helical and curved spiral-shaped bacteria exist as slender spirochetes, spirillum, and bent rods (see Figure 6.1). Bacterial cells are usually measured in microns (μ) or micrometers (μm); $1\ \mu\text{m} = 0.001$ or $1/1000$ of a millimeter (mm). A typical rod-shaped coliform bacterial cell is about $2\ \mu\text{m}$ long and about $0.7\ \mu\text{m}$ wide. The size of a cell changes with time due to growth and death. Viewed under a microscope, bacterial cells may be seen as separate (individual) cells or as cells in groupings. Depending on the species, cells may appear in pairs (diploids), chains, groups of four (tetrads), cubes (sarcinae), or clumps. Long chains of cocci result when cells adhere after repeated divisions in one plane; this pattern is seen in the genera *Enterococcus* and *Lactococcus*. In the genus *Sarcina*, however, cocci divide in three planes, producing cubical packets of eight cells (tetrads). The exact shape of rod-shaped cells varies, especially at the end of the rod. The end of the rod may be flat, cigar shaped, rounded, or bifurcated. Although many rods do occur singly, they may remain together after division to form pairs or chains (see Figure 6.1). Frequently, these characteristic arrangements are useful in bacterial identification.

structure of the bacterial cell The structural form and various components of the bacterial cell are probably best understood by referring to the simplified diagram of a rod-form bacterium shown in Figure 6.2. When studying the figure, keep in mind that cells of different species may differ greatly, both in structure and chemical composition; for this reason, no typical bacterium exists. Figure 6.2 shows a generalized bacterium used for the discussion that follows; however, not all bacteria have all of the features shown in the figure, and some bacteria have structures not shown in the figure.

Capsules Bacterial capsules (see Figure 6.2) are organized accumulations of gelatinous material on cell walls, in contrast to slime layers (a water secretion that adheres loosely to the cell wall and commonly diffuses into the cell), which are unorganized accumulations of similar material. Macrocapsules are usually thick enough to be seen under an ordinary light microscope, but thinner capsules known as microcapsules can be detected only by electron microscopy (Singleton and Sainsbury, 1994). The production of capsules is determined largely by genetics as well as environmental conditions and depends on the presence or absence of capsule-degrading enzymes and other growth factors. Varying in composition, capsules are mainly composed of water; the organic contents are made up of complex polysaccharides, nitrogen-containing substances, and polypeptides. Capsules confer several advantages when bacteria grow in their normal habitat; for example, they help to (1) prevent desiccation, (2) resist phagocytosis by host phagocytic cells, (3) prevent infection by bacteriophages, and (4) aid bacterial attachment to tissue surfaces in plant and animal hosts or to surfaces of solid objects in aquatic environments. Capsule formation often correlates with pathogenicity (Spellman, 2008).

Flagella Many bacteria are motile, and this ability to move independently is usually attributed to a special structure, the flagella (singular: flagellum). Depending on species, a cell may have a single flagellum (see Figure 6.2) (monotrichous bacteria; trichous means “hair”), one flagellum at each end (amphitrichous bacteria; amphi means “on both sides”), a tuft of flagella at one or both ends (lophotrichous bacteria; lopho

means “tuft”), or flagella that arise all over the cell surface (peritrichous bacteria; *peri* means “around”). A flagellum is a threadlike appendage extending outward from the plasma membrane and cell wall. Flagella are slender, rigid locomotor structures, about 20 μm across and up to 15 or 20 μm long. Flagellation patterns are very useful in identifying bacteria and can be seen by light microscopy, but only after the flagella have been stained with special techniques designed to increase their thickness. The detailed structure of flagella can be seen only in an electron microscope. Bacterial cells benefit from flagella in several ways. Flagella can increase the concentration of nutrients or decrease the concentration of toxic materials near the bacterial surfaces by causing a change in the flow rate of fluids. They can also disperse flagellated organisms to areas where colony formation can take place. The main benefit of flagella to organisms is the improved ability to flee from areas that might be harmful.

Cell Wall The main structural component of most procaryotes is the rigid cell wall. Functions of the cell wall include (1) providing protection for the delicate protoplast from osmotic lysis (bursting); (2) determining the shape of a cell; (3) acting as a permeability layer that excludes large molecules and various antibiotics and plays an active role in regulating the intake of ions by the cell; and (4) providing a solid support for flagella. Cell walls of different species may differ greatly in structure, thickness, and composition. The cell wall accounts for about 20 to 40% of the dry weight of a bacterium. Gram Stain Microbial cells are nearly transparent when observed by light microscopy and thus are difficult to see. The most common method for observing cells is by the use of stained preparations. Dyes are used to stain cells, which increases their contrast so they can be more easily observed in a light microscope. Simple cell-staining techniques depend on the fact that bacterial cells differ chemically from their surroundings and thus can be stained to contrast with their environment. Microbes also differ from one another chemically and physically and therefore may react differently to a given staining procedure. This is the basic principle of differential staining—so named because this type of procedure does not stain all kinds of cells equally. The Gram staining procedure was developed in the 1880s by Hans Christian Gram, a Danish bacteriologist. Gram discovered that microbes could be distinguished from surrounding tissue and observed that some bacterial cells exhibit an unusual resistance to decolorization. He used this observation as the basis for a differential staining technique. Gram differentiation is based on the application of a series of four chemical reagents: primary stain, mordant, decolorizer, and counterstain. The purpose of the primary stain, crystal violet, is to impart a blue or purple color to all organisms regardless of their Gram reaction. This is followed by the application of Gram’s iodine, which acts as a mordant (fixer) that enhances the union between the crystal violet stain and its substrate by forming a complex. The decolorizing solution of 95% ethanol extracts the complex from certain cells more readily than others. In the final step, a counterstain (safranin) is applied to reveal organisms previously decolorized by removal of the complex. Those organisms retaining the complex are Gram positive (blue or purple), whereas those losing the complex are Gram negative (red or pink).

Gram-Positive Cell Walls Normally, the thick, homogeneous cell walls of Grampositive bacteria are composed primarily of a complex polymer, which often contains linear heteropolysaccharide chains bridged by peptides to form a three-dimensional netlike structure and envelop the protoplast. Gram-positive cells usually also contain large amounts of teichoic acids—typically, substituted polymers or ribitol phosphate and glycerol phosphate. Amino acids or sugars such as glucose are attached to the ribitol and glycerol groups. Teichoic acids are negatively charged and help give the Gram-positive cell wall its negative charge.

Growth conditions can affect the composition of the cell wall; for example, the availability of phosphates affects the amount of teichoic acid in the cell wall of *Bacillus*. Teichoic acids are not present in Gram-negative bacteria.

Gram-Negative Cell Walls Gram-negative cell walls are much more complex than Gram-positive walls. The Gram-negative wall is about 20 to 30 μm thick and has a distinctly layered appearance under the electron microscope. The thin inner layer consists of peptidoglycan and constitutes no more than 10% of the wall weight. In *Escherichia coli*, the Gram-negative walls are about 1 μm thick and contain only one or two layers of peptidoglycan. The outer membrane lies outside the thin peptidoglycan layer and is essentially a lipoprotein bilayer. The outer membrane and peptidoglycan are so firmly linked by this lipoprotein that they can be isolated as one unit.

Plasma Membrane (Cytoplasmic Membrane) Surrounded externally by the cell wall and composed of a lipoprotein complex, the plasma membrane is the critical barrier separating the inside from the outside of the cell. About 7 to 8 nm thick and comprising 10 to 20% of the dry weight of a bacterium, the plasma membrane controls the passage of all material into and out of the cell. The inner and outer faces of the plasma membrane are embedded with water-loving (hydrophilic) lips, whereas the interior is hydrophobic. Control of material into the cell is accomplished by screening, as well as by electric charge. The plasma membrane is the site of the surface charge of the bacteria. In addition to serving as an osmotic barrier that passively regulates the passage of material into and out of the cell, the plasma membrane participates in the active transport of various substances into the bacterial cell. Inside the membrane, many highly reactive chemical groups guide the incoming material to the proper points for further reaction. This active transport system provides bacteria with certain advantages, including the ability to maintain a fairly constant intercellular ionic state in the presence of varying external ionic concentrations. In addition to participating in the uptake of nutrients, the cell membrane transport system participates in waste excretion and protein secretions.

Cytoplasm Within a cell and bounded by the cell membrane is a complicated mixture of substances and structures known as the cytoplasm. The cytoplasm is a water-based fluid containing ribosomes, ions, enzymes, nutrients, storage granules (under certain circumstances), waste products, and various molecules involved in synthesis, energy metabolism, and cell maintenance.

Mesosome An intracellular structure commonly found in the bacterial cytoplasm is the mesosome. Mesosomes are invaginations of the plasma membrane in the shape of tubules, vesicles, or lamellae. Their exact function is unknown. Many bacteriologists believe that mesosomes are artifacts generated during the fixation of bacteria for electron microscopy (Singleton and Sainsbury, 1994).

Nucleoid (Nuclear Body or Region) The nuclear region of the procaryotic cell is primitive and a striking contrast to that of the eucaryotic cell. Procaryotic cells lack a distinct nucleus; instead, the function of the nucleus is carried out by a single, long, double strand of deoxyribonucleic acid (DNA) that is efficiently packaged to fit within the nucleoid. The nucleoid is attached to the plasma membrane. A cell can have more than one nucleoid when cell division occurs after the genetic material has been duplicated.

Ribosomes The bacterial cytoplasm is often packed with ribosomes, which are minute, rounded bodies made of ribonucleic acid (RNA) that are loosely attached to the plasma membrane. Ribosomes are estimated to account for about 40% of the dry weight of a bacterium; a single cell may have as many as 10,000 ribosomes. Ribosomes are the site of protein synthesis and are part of the translation process; they

are commonly called the “powerhouses of the cell.” Inclusions (or storage granules) are often seen within bacterial cells. Some inclusion bodies are not bound by a membrane and lie free in the cytoplasm. Other inclusion bodies are enclosed by a single-layer membrane about 2 to 4 μm thick. Many bacteria produce polymers that are stored as granules in the cytoplasm.

chemical composition of a bacterial cell Bacteria, in general, are composed primarily of water (about 80%) and of dry matter (about 20%). The dry matter consists of both organic (90%) and inorganic (10%) components. All basic elements from protoplasm must be derived from the liquid environment, and if the environment is deficient in vital elements the cell shows a characteristic lack of development. Note: The normal growth of a bacterial cell in excess nutrients results in a cell of definite chemical composition. The growth, however, involves a coordinated increase in the mass of its constituent parts, not solely an increase in total mass.

metabolism Metabolism refers to the bacteria’s ability to grow in any environment. The metabolic process refers to the chemical reactions that occur in living cells. In this process, anabolism works to build up cell components and catabolism breaks down or changes the cell components from one form to another. Metabolic reactions require energy, as do locomotion and the uptake of nutrients. Many bacteria obtain their energy by processing chemicals from the environment through chemosynthesis. Other bacteria obtain their energy from sunlight through photosynthesis.

Chemosynthesis Chemosynthesis is the synthesis of organic substances such as food nutrients using the energy of chemical reactions. Bacteria that obtain carbon from carbon dioxide are called autotrophic. Bacteria that obtain carbon through organic compounds are called heterotrophic (see Figure 6.3).

Autotrophic Bacteria Organisms that can synthesize organic molecules necessary for growth from inorganic compounds using light or another source of energy are autotrophs. For their carbon requirements, autotrophs are able to use (fix) carbon dioxide to form complex organic compounds. **Heterotrophic Bacteria** Most bacteria are not autotrophic. They cannot use carbon dioxide as a major source of carbon and therefore must rely upon the presence of more reduced, complex molecules (mostly derived from other organisms) for their carbon supply. Bacteria that need complex carbon compounds are heterotrophs. Heterotrophs use a vast range of carbon sources, including fatty acids, alcohols, sugars, and other organic substances. Heterotrophic bacteria are widespread in nature and include all those species that cause disease in humans, other animals, and plants.

classification Classifying bacteria and other microbes is complicated because of the enormous variety of microorganisms that differ widely in their metabolic and structural properties. Some microorganisms are plant like, others are animal like, and still others are totally different from all other forms of life. As an example of the classification process, let’s consider microorganisms in terms of their activities. Bacteria can be classified as aerobic, anaerobic, or facultative. Aerobic bacteria must have oxygen to live. At the other extreme, that same oxygen would be toxic to an anaerobe (bacteria that live without oxygen). Facultative bacteria are capable of growth under aerobic or anaerobic conditions.

Because bacteria have so many forms, their proper classification or identification requires applying systematic procedures to grow, isolate, and identify the individual varieties. These procedures are highly specialized and technical. Ultimately, bacteria are characterized based on observation and experience. Fortunately, certain classification criteria have been established to help in the sorting process (Singleton, 1992):

1. Shape
2. Size and structure
3. Chemical activities
4. Types of nutrients needed
5. Form of energy used
6. Physical conditions needed for growth
7. Ability to cause disease (pathogenic or nonpathogenic)
8. Staining behavior (Gram stain)

Based on these criteria and on observation and experience, it is possible to identify bacteria from descriptions published in the latest Bergey's Manual of Determinative Bacteriology.

fecal coliform bacteria: indicator organisms Fecal coliform are bacteria that live in the digestive tract of warm-blooded animals. They are excreted in the solid waste of humans and other mammals. Fecal coliform generally enter the water in the following ways:

- Improperly treated wastewater from municipal systems, septic systems, or combined sewer overflows
- Runoff from animal stockyards, pastures, and rangeland
- Inadequately captured wastes from human activities such as construction or camping

Fecal coliforms generally do not pose a danger to people or animals. Where fecal coliforms are present, however, disease-causing bacteria are usually also present. Unlike fecal coliforms, disease-causing bacteria generally do not survive outside the body of animals long enough in the water to be detected. This makes their direct monitoring difficult. Drinking water practitioners and public health officials consider the presence of fecal coliform an indicator of disease bacteria in the water. The presence of fecal coliforms tends to affect humans more than it does aquatic creatures, though not exclusively. Bacteria associated with fecal coliforms can cause significant disease in humans, such as diarrhea, dysentery, cholera, and typhoid fever. Some of these bacteria can also cause infection in open wounds. Untreated fecal material that contains fecal coliforms adds excess organic material to the water; the decay of this material depletes oxygen in the water, which may kill fish and other aquatic life. Reduction of fecal coliforms in wastewater may require the use of chlorine and other disinfectant chemicals; such materials may kill bacteria essential to the proper balance of the aquatic environment, endangering the survival of species dependent on those bacteria. Higher levels of fecal coliform require higher levels of chlorine, further threatening those aquatic organisms.

Total Coliform Rule The Total Coliform Rule (40 CFR 141.21) is the part of the Safe Drinking Water Act that addresses detection and removal of bacterial contamination in drinking water. The Total Coliform Rule applies to every public water system. Each public water system must take at least one coliform sample every year and submit the results of that sample to the state Drinking Water Program for compliance purposes.

Fecal Coliform Testing Procedures Extensive research has been conducted and is ongoing in an attempt to compare the presence and the significance of specific organisms in water to the traditional coliform

group and waterborne diseases, with the goal of pinpointing the best indicator of contamination in water. The search continues for a quick, economic, reliable determination for possible use in routine examination, or at least during outbreaks of the waterborne diseases. Federal regulations cite two approved methods for the determination of fecal coliform in water: (1) the multiple-tube fermentation (MTF) technique for members of the coliform group, and (2) the membrane filtration (MF) technique for members of the coliform group. The multiple-tube method is still used in many labs, because the membrane filtration method is not applicable to turbid samples; however, the membrane filtration method takes less time and provides a more direct count of the coliforms than the multiple-tube method does. It also requires less laboratory equipment. The bottom line? Drinking water practitioners need to understand the essential differences between these two tests, but before those differences are explained it is necessary to lay some groundwork by explaining testing preparations. Note: Both methods are still recognized as sufficiently reliable with relatively simple techniques and economic equipment to be run as often as required by the monitoring activity of water quality control. We discuss each of these procedures briefly in the following sections; however, do not attempt to perform the fecal coliform test using the summary information provided within this text. Instead, refer to the appropriate references cited in the Federal Register or the current Standard Methods and Procedures for a complete discussion of these procedures. Note: Because the MF procedure can yield low or highly variable results for chlorinated water, the U.S. Environmental Protection Agency (USEPA) requires verification of results using the most probable number (MPN) procedure to resolve any controversies.

Testing Preparations Whenever microbiological testing of water samples is performed, certain general considerations and techniques are required. Because these considerations are similar for each test procedure, we review them here prior to our specific discussion of the two test methods:

- **Reagents and media**—All reagents and media used in performing microbiological tests on water samples must meet the standards specified in references cited in federal regulations.
- **Reagent-grade water**—Deionized water that is tested annually and found to be free of dissolved metals and bactericidal or inhibitory compounds is preferred for use in preparing culture media and test reagents, although distilled water may be used.
- **Chemicals**—All chemicals used in fecal coliform monitoring must be American Chemical Society (ACS) reagent grade or equivalent.
- **Media**—To ensure uniformity in the test procedures the use of dehydrated media is recommended. Sterilized prepared media in sealed test tubes, ampules, or dehydrated media pads are also acceptable for use in these tests.
- **Glassware and disposable supplies**—All glassware, equipment, and supplies used in microbiological testing should meet the standards specified in references cited in federal regulations.

All glassware used for bacteriological testing must be thoroughly cleaned using a suitable detergent and hot water. The glassware should be rinsed with hot water to remove all traces of detergent residue and finally rinsed with distilled water. Laboratories should use a detergent certified to meet bacteriological standards or at a minimum should rinse all glassware after washing with two tap water rinses followed by five distilled-water rinses. For sterilization of equipment, a hot-air sterilizer or autoclave can be used. When using the hot-air sterilizer, all equipment should be wrapped in high-quality (Kraft) paper or placed in containers prior to hot-air sterilization. All glassware (except those in metal containers) should be sterilized for a minimum of 60 minutes at 170°C. Sterilization of glassware in metal containers requires a minimum of 2 hours. Hot-air sterilization cannot be used for liquids. Sample bottles, dilution water, culture

media, and glassware may also be sterilized by autoclaving at 121°C for 15 minutes. Dilution water used for making sample serial dilutions is prepared by adding 1.25 mL of stock buffer solution and 5.0 mL of magnesium chloride solution to 1000 mL of distilled or deionized water. The stock solutions of each chemical should be prepared as outlined in the references cited in federal regulations. The dilution water is then dispensed in sufficient quantities to produce 9 or 99 mL in each dilution bottle following sterilization. If the membrane filtration procedure is used, additional 60 to 100-mL portions of dilution water should be prepared and sterilized to provide the rinse water required by the procedure. At times, the density of the organisms in a sample makes accurately determining the actual number of organisms in the sample difficult. When this occurs, the sample size may need to be reduced to as little as 1 millionth of a milliliter. To obtain such small volumes, a technique known as serial dilutions is used.

Multiple Tube Fermentation Technique The multiple-tube fermentation (MTF) technique for fecal coliform testing of water, solid, or semisolid samples is based on the fact that coliform organisms can use lactose (the sugar occurring in milk) as food and produce gas in the process. In waste testing, the procedure normally consists of presumptive, confirming, and completed phases. It is recognized as the method of choice for any samples that may be controversial (i.e., enforcement related). When multiple tubes are used in the fermentation technique, results of the examination of replicate tubes and dilutions are reported in terms of the most probable number (MPN) of organisms present. This number, based on certain probability formulas, is an estimate of the mean density of coliforms in the sample. Coliform density provides the best assessment of water treatment effectiveness and the sanitary quality of untreated water. The production of gas in a single fermentation tube may indicate the presence of coliforms, but it gives no indication as to the concentration of bacteria in the sample; that is, a coliform count cannot be obtained directly. The gas bubble created could be the result of one bacterium or millions. The precision of each test depends on the number of tubes used. The most satisfactory information will be obtained when the largest sample inoculum shows no gas at all in a majority of the tubes. Bacterial density can be estimated mathematically or derived from a table using the number of positive tubes in multiple dilutions. The number of sample portions selected is governed by the desired precision of the result. MPN tables are based on the assumption of a Poisson (random) distribution; however, if the sample is not adequately shaken before the portions are removed or if clumping of bacterial cells occurs, the MPN value will underestimate the actual bacterial density. The technique utilizes a two-step incubation procedure. The sample dilutions are first incubated in lauryl (sulfonate) tryptose broth for 24 to 48 hours (presumptive phase). Positive samples are then transferred to EC broth and incubated for an additional 24 hours (confirming phase). Positive samples from this second incubation are used to statistically determine the MPN from the appropriate reference chart. A single-media, 24-hour procedure is also acceptable. In this procedure, sample dilutions are inoculated in A-1 media and incubated for 3 hours at 35°C, then incubated for 21 hours at 44.5°C. Positive samples from these inoculations are then used to statistically determine the MPN value from the appropriate chart.

Fecal Coliform MPN Presumptive Test Procedure

1. Prepare dilutions and inoculate five fermentation tubes for each dilution.
2. Cap all tubes and transfer to incubator.
3. Incubate 24 ± 2 hr at $35 \pm 0.5^\circ\text{C}$.
4. Examine tubes for gas: Gas present (positive test)—transfer. No gas—continue incubation. Incubate for a total time of 48 ± 3 hr at $35 \pm 0.5^\circ\text{C}$.
5. Examine tubes for gas: Gas present (positive test)—transfer. No gas (negative test).

Note: Keep in mind that the fecal coliform MPN confirming procedure and the fe-

cal coliform procedure using the A-1 broth test are used to determine the most probable number per 100 mL. The MPN procedure for fecal coliform determination requires a minimum of three dilutions with five tubes per dilution.

Calculation of Most Probable Number per 100 mL Most probable number test calculations require the selection of a valid series of three consecutive dilutions. The number of positive tubes in each of the three selected dilution inoculations is used to determine the MPN/100 mL. When selecting the dilution inoculations to be used in the calculation, each dilution is expressed as a ratio of positive tubes per tubes inoculated in the dilution (e.g., three positive per five inoculated, or 3/5). Several rules must be followed in determining the most valid series of dilutions. In the following examples, four dilutions were used for the test.

1. Using the confirming test data, select the highest dilution showing all positive results (no lower dilution showing less than all positive) and the next two higher dilutions.
2. If a series shows all negative values (with the exception of one dilution), select the series that places the only positive dilution in the middle of the selected series.
3. If a series shows a positive result in a dilution higher than the selected series (using rule 1), it should be incorporated into the highest dilution of the selected series.

After selecting the valid series, the MPN/100 mL is determined by locating the selected series on the MPN reference chart. If the selected dilution series matches the dilution series of the reference chart, the MPN value from the chart is the reported value for the test. If the dilution series used for the test does not match the dilution series of the chart, the test result must be calculated. ? EXAMPLE 6.1

Solution: 1. Select the highest dilution (tube with the lowest amount of sample) with all positive tubes (1.0-mL dilution). Select the next two higher dilutions (0.1 mL and 0.01 mL). In this case, the selected series will be 5–3–1. 2. Include any positive results in dilutions higher than the selected series (0.001-mL dilution, 1/5). This changes the selected series to 5–3–2. 3. Using the Sample Volume columns in Table 6.4, locate this series (5–3–2). 4. Read the MPN value from the fourth column (140).

1. Note that, in Table 6.4, the dilution series begins with 10 mL. For this test, the series begins with 1.0 mL.

MPN/100 mL ? 140 MPN/100 mL ? 10 mL ? 1400 MPN/100 mL 1 mL Membrane Filtration Technique

The membrane filtration (MF) technique is highly reproducible, can be used to test relatively large volumes of sample, and yields numerical results more rapidly than the multiple-tube procedure. MF is extremely useful in monitoring drinking water and a variety of natural waters; however, the technique does have limitations, particularly when testing waters with high turbidity or non-coliform (background) bacteria. For such waters, or when the MF technique has not been used previously, conducting parallel tests with the MTF technique to demonstrate applicability and comparability is desirable. Note: As related to the MF technique, the coliform group may be defined as being comprised of aerobic and many facultative anaerobic, Gram-negative, non-spore-forming, rod-shaped bacteria that develop red colonies with a metallic sheen within 24 hours at 35°C on an Endo-type medium. Some members may produce dark red,

muroid, or nucleated colonies without a metallic sheen. When verified these are classified as atypical coliform colonies. When purified cultures of coliform bacteria are tested, they produce a negative cytochrome oxidase (CO) and a positive ONPG reaction for β -galactosidase. Generally, all red, pink, blue, white, or colorless colonies lacking sheen are considered noncoliforms by this technique.

The membrane filtration technique uses a specially designed filter pad with uniformly sized pores (openings) small enough to prevent bacteria from entering the filter. A measured volume of sample is drawn through the filter pad by applying a partial vacuum. The special pad retains the bacteria on its surface, while allowing the water to pass through. Note: In the MF method, the number of coliforms is estimated by the number of colonies grown. In order to use the MF procedure for chlorinated effluents, you must be able to demonstrate that it gives information comparable to that obtained by the MTF test. The MF procedure uses an enriched lactose medium and incubation temperature of $44.5 \pm 0.2^\circ\text{C}$ for selectivity and gives 93% accuracy in differentiating between coliforms found in the feces of warm-blooded animals and those from other environmental sources. Because incubation temperature is critical, submerge water-proofed (e.g., plastic bag enclosures) MF cultures in a water bath for incubation at the elevated temperature, or use an appropriate, accurate solid heat sink incubator. Alternatively, use an equivalent incubator that will hold the 44.5°C temperature within 0.2°C throughout the chamber over a 24-hour period while located in an environment of ambient air temperatures ranging from 5 to 35°C .

Materials and Culture Medium 1. m-FC media—The need for uniformity dictates the use of dehydrated media. Never prepare media from basic ingredients when suitable dehydrated media are available. Follow manufacturer's directions for rehydration. Commercially prepared media in liquid form (sterile ampule or other) may also be used if known to give equivalent results. **2. Culture dishes**—Use tight-fitting plastic dishes because the MF cultures are submerged in a water bath during incubation. Enclose groups of fecal coliform cultures in plastic bags or seal individual dishes with waterproof (freezer) tape to prevent leakage during submersion. **3. Incubator**—The specificity of the fecal coliform test is related directly to the incubation temperature. Static air incubation may be a problem in some types of incubators because of potential heat layering within the chamber and the slow recovery of temperature each time the incubator is opened during daily operations. To meet the need for greater temperature control, use a water bath, a heat-sink incubator, or a properly designed and constructed incubator giving equivalent results. A temperature tolerance of $44.5 \pm 0.2^\circ\text{C}$ can be obtained with most types of water baths equipped with a gable top for the reduction of heat and water losses. A circulating water bath is excellent but may not be essential to this test, if the maximum permissible variation of 0.2°C in temperature can be maintained with other equipment. **Procedure 1. Sample filtration** a. Select a filter and aseptically separate it from the sterile package. b. Place the filter on the support plate with the grid side up. c. Place the funnel assembly on the support; secure as needed. d. Pour 100 mL of sample or serial dilution onto the filter; apply vacuum. Note: The appropriate sample size and serial dilution should result in the growth of 20 to 60 fecal coliform colonies on at least one filter. The selected dilutions must also be capable of showing permit exclusions. e. Allow all of the liquid to pass through the filter. f. Rinse the funnel and filter with three portions (20 to 30 mL) of sterile, buffered dilution water. (Allow each portion to pass through the filter before the next addition.) g. Remove the filter funnel and aseptically transfer the filter, grid side up, onto the prepared media. Note: Filtration units should be sterile at the start of each filtration series and should be sterilized again if the series is interrupted for 30 minutes or more. A rapid interim sterilization can be accomplished

by 2 minutes' exposure to ultraviolet (UV) light, flowing steam, or boiling water. 2. Incubation a. Place absorbent pad into culture dish using sterile forceps. b. Add 1.8 to 2.0 mL m-FC media to the absorbent pad.

1. Discard any media not absorbed by the pad.
2. Filter sample through sterile filter.
3. Remove filter from assembly and place on absorbent pad (grid up).
4. Cover culture dish.
5. Seal culture dishes in a weighted plastic bag.
6. Incubate filters in a water bath for 24 hours at $44.5 \pm 0.2^\circ\text{C}$.

Colony Counting Upon completion of the incubation period, the surface of the filter will have growths of both fecal coliform and non-fecal coliform bacteria colonies. The fecal coliform will appear blue in color, whereas the non-fecal coliform colonies will appear gray or cream colored. To count the colonies, the entire surface of the filter should be scanned using a $10\times$ to $15\times$ binocular, wide-field dissecting microscope. The desired range of colonies for the most valid fecal coliform determination is 20 to 60 colonies per filter. If multiple sample dilutions are used for the test, counts for each filter should be recorded on the laboratory data sheet.

- Too many colonies—Filters that show a growth over the entire surface of the filter with no individually identifiable colonies should be recorded as “confluent growth.” Filters that show a very high number of colonies (greater than 200) should be recorded as “too numerous to count” (TNTC).
- Not enough colonies—If no single filter meets the desired minimum colony count (20 colonies), the sum of the individual filter counts and the respective sample volumes can be used in the formula to calculate the colonies per 100 mL.

Note: In each of these cases, adjustments in sample dilution volumes should be made to ensure that future tests meet the criteria for obtaining a valid test result.

Calculation The fecal coliform density can be calculated using the following formula:

Colonies/100 mL = $\frac{\text{Colonies counted} \times 100 \text{ mL}}{(\text{6.2}) \text{ Sample volume (mL)}}$

Solution: 1. Influent sample—Select the influent sample filter that has a colony count in the desired range (20 to 60). Because one filter meets this criterion, the remaining influent filters that did not meet the criterion are discarded. Colonies/100 mL = $\frac{48 \text{ colonies} \times 100 \text{ mL}}{48,000 \text{ colonies/100 mL} \times 0.1 \text{ mL}}$ 2. Effluent sample—Because none of the filters for the effluent sample meets the minimum test requirement, the colonies per 100 mL must be determined by totaling the colonies on each filter and the sample volumes used for each filter. Total colonies = $10 + 5 + 3 + 18 = 36$ colonies Total sample = $10.0 \text{ mL} + 1.0 \text{ mL} + 0.1 \text{ mL} + 11.1 \text{ mL} = 22.2 \text{ mL}$ Colonies/100 mL = $\frac{36 \text{ colonies} \times 100}{22.2} = 162 \text{ colonies/100 mL}$

Note: The USEPA criterion for fecal coliform bacteria in bathing waters is a logarithmic mean of 200 per 100 mL, based on a minimum of 5 samples taken over a 30-day period, with not more than 10% of the total samples exceeding 400 per 100 mL. Because shellfish may be eaten without being cooked, the strictest coliform criterion applies to shellfish cultivation and harvesting. The USEPA criterion states that the

mean fecal coliform concentration should not exceed 14 per 100 mL, with not more than 10% of the samples exceeding 43 per 100 mL.

Interferences Large amounts of turbidity, algae, or suspended solids may interfere with this technique by blocking the filtration of the sample through the membrane filter. Dilution of these samples to prevent this problem may make the test inappropriate for samples with low fecal coliform densities, as the sample volumes after dilution may be too small to give representative results. The presence of large amounts of non-coliform group bacteria in the samples may also prohibit the use of this method.

Geometric Mean Calculation Many National Pollutant Discharge Elimination System (NPDES) discharge permits require fecal coliform testing. Results for fecal coliform testing must be reported as a geometric mean (average) of all the test results obtained during a reporting period. A geometric mean, unlike an arithmetic mean or average, dampens the effect of very high or low values that otherwise might cause a non-representative result. Note: Current regulatory requirements prohibit the reporting of no MPN or colonies. If the test result does not produce any positive results or colonies, it must be reported as <1 (less than 1). In cases where test results are reported as 0 or <1, a value of 1 should be used to calculate the geometric mean. This substitution does not affect the result of the calculation; it just ensures that the data are entered into the calculation in a usable form.

Calculation of the geometric mean can be performed by one of two methods. Both methods require a calculator capable of performing more advanced calculations. The first method requires a calculator that is capable of determining the n th root of a number (n = the number of values used in the calculation). The general formula for this method of calculating the geometric mean is

Geometric mean ? This equation states that the geometric mean can be found by multiplying all of the data points for a given reporting period together and taking the n th root of this product.

? **EXAMPLE 6.3** Problem: Given the data in the chart below, determine the geometric mean using the n th root method. Week 1 5 colonies/100 mL Week 2 7 colonies/100 mL Week 3 90 colonies/100 mL Week 4 1000 colonies/100 mL Solution:

Geometric mean ? ? ? 42 colonies/100 mL

The second method for calculation of the geometric mean requires a calculator that can compute logarithms (log) and antilogarithms (antilog): Procedure 1. If there are any reported values of 0, replace them with <1. 2. Using the calculator, determine the logarithm of each test result. 3. Add the logarithms of all of the test results. 4. Divide the sum by the number of test results (n). 5. Enter this number into the calculator. 6. Press “2nd” or “INV” then “LOG.” 7. See the geometric mean displayed on the calculator.

? **EXAMPLE 6.4** Problem: Given the data below, determine the geometric mean. Week 1 12 MPN per 100 mL Week 2 28 MPN per 100 mL

Week 3 37 MPN per 100 mL Week 4 25 MPN per 100 mL

VIRUSES Viruses are parasitic particles—the smallest living infectious agents known. Because they are parasitic entities, they are not cellular (have no nucleus, cell membrane, or cell wall), they are unable to multiply or adapt to the hostile water environment, and they lack a living host. They multiply only within living cells (hosts) and are totally inert outside of living cells, but they still can survive in the environment. Viruses differ from living cells in at least three ways: (1) they are unable to reproduce independently of cells and cannot carry out cell division; (2) they possess only one type of nucleic acid, either DNA or RNA; and (3) they have a simple acellular organization (Prescott et al., 1993). Viruses can infect humans (it only takes a single virus particle to infect a

host) through recently contaminated drinking water, the relativity of time being connected with the survival ability of the virus in natural and manmade hostile environments. At present, over 100 virus types are known to occur in human feces, and an infected person may excrete as many as 10⁶ infectious particles in 1 gram of feces; thus, the potential for contamination is very great. Of those contacting viruses, only a small percentage are infected, and of those infected only about 2% may become recognizably ill. Assuming a 1% infection rate and a 2% illness rate, this means that 1 in every 5000 persons coming in contact with a virus becomes ill, a very high rate if water is contaminated with fecal matter (Tchobanoglous and Schroeder, 1987). Isolation of viruses has improved considerably over the past several decades. They can be controlled by chlorination, but at much higher levels than are necessary to kill bacteria. The viruses examined by the drinking water practitioner are practically limited to enteric viruses (infections of the intestinal tract). Some viruses that may be transmitted by water include infectious hepatitis, adenovirus, polio, coxsackie, echoviruses, and Norwalk agent. A virus that infects a bacterium is called a bacteriophage

bacteriophage Lewis Thomas (1974) observed that when humans “catch diphtheria it is a virus infection, but not of us.” In other words, what humans have really caught is a bacterium that is infected by the virus—humans simply “blundered into someone else’s accident.” The toxin of diphtheria bacilli is produced by organisms that have been infected with a bacteriophage (phage), which is any viral organism whose host is a bacterium. Most bacteriophage research has been carried out on the bacterium *Escherichia coli*, which is one of the Gram-negative bacteria that water specialists are concerned with because it is a typical coliform.

Indicator Viruses Considerable research has been accomplished in the last several decades in an attempt to determine certain viruses as indicator viruses. In Volume 1 of *Drinking Water and Health*, the National Academy of Sciences (NAS, 1977) reached the following conclusions:

1. The presence of infecting viruses in drinking water is a potential hazard to public health, and no valid basis exists upon which a no-effect concentration of viral contamination in finished drinking water might be established. Note: This statement in no way should be interpreted to mean that viruses are not removed by conventional treatment and disinfection. On the contrary, drinking water produced by an effective conventional treatment and distributed after disinfection is expected to have significantly reduced concentrations of viruses inactivated by the treatment.
2. Continued testing for viral contamination of potable water should be carried out with the facilities and skills of a wide variety of research establishments, both inside and outside of government, and methodology for virus testing should be improved.
3. The bacteriological monitoring methods currently prescribed or recommended in this report (coliform count and standard plate count) are the best indicators available for routine use in evaluating the presence in water of intestinal pathogens, including viruses.

In 1987, the USEPA concluded that measuring the level of enteric viruses in drinking water is not economically or technologically feasible because currently acceptable methods require levels of expertise that utility personnel normally do not possess, and the methods would be too expensive if analyzed by private laboratories.

Validation procedures have not yet been established. Continuous monitoring would be required, but monitoring does not provide advance notice to ensure the safety of drinking water at the consumer's tap (DeZuane, 1997).

PROTOZOA The protozoa ("first animals") are a large group (more than 50,000 known species) of eucaryotic organisms that have adapted a form or cell to serve as the entire body. In fact, all protozoa are single-celled organisms. Typically, they lack cell walls but have a plasma membrane that is used to take in food and discharge waste. They can exist as solitary or independent organisms (e.g., stalked ciliates such as *Vorticella*), or they can colonize (e.g., the sedentary *Carchesium*). Protozoa are microscopic and get their name because they employ the same type of feeding strategy as animals. Most are harmless, but some are parasitic. Some forms have two life stages: active trophozoites (capable of feeding) and dormant cysts. As unicellular eucaryotes, protozoa cannot be easily defined because they are diverse and in most cases only distantly related to each other (Patterson and Hedley, 1992). Each protozoa is a complete organism and contains the facilities for performing the body functions for which vertebrates have many organ systems. Certain types of protozoa can cause disease. Of particular interest to the drinking water practitioner are *Entamoeba histolytica* (amebic dysentery and amebic hepatitis), *Giardia lamblia* (giardiasis), *Cryptosporidium* (cryptosporidiosis), and *Cyclospora* (cyclosporiasis). Sewage contamination transports eggs, cysts, and oocysts of parasitic protozoa and helminths (tapeworms, hookworms, etc.) into raw supplies, leaving water treatment and disinfection as the means by which to diminish the risk of contaminated water for the consumer. To prevent the occurrence of *Giardia* and *Cryptosporidium* in surface water supplies and to address increasing problems with waterborne diseases, the USEPA implemented its Surface Water Treatment Rule (SWTR) in 1989. The rule requires both filtration and disinfection of all surface water supplies as a means of primarily

controlling *Giardia* and enteric viruses. Since implementation of the SWTR, the USEPA has also recognized that *Cryptosporidium* is an agent of waterborne disease (Badenock, 1990). In its next series of surface water regulations (in 1996), the USEPA included *Cryptosporidium*. To test the need for and effectiveness of the Surface Water Treatment Rule, a study was conducted on the occurrence and distribution of *Giardia* and *Cryptosporidium* organisms in raw water supplies to 66 surface water filter plants (LeChevallier et al., 1991). These plants were located in 14 states and a Canadian province. A combined immunofluorescence test indicated that cysts and oocysts were widely dispersed in the aquatic environment. *Giardia* was detected in more than 80% of the samples. *Cryptosporidium* was found in 85% of the sample locations. Taking into account several variables, *Giardia* or *Cryptosporidium* were detected in 97% of the raw water samples. After evaluating their data, the researchers came to the conclusion that the Surface Water Treatment Rule may have to be upgraded (subsequently, it has been) to require additional treatment (Spellman, 2008).

Giardia *Giardia lamblia* (also known as the hiker's/traveler's scourge or disease) is a microscopic parasite that can infect warm-blooded animals and humans. Although *Giardia* was discovered in the 19th century, not until 1981 did the World Health Organization (WHO) classify *Giardia* as a pathogen. An outer shell called a cyst allows *Giardia* to survive outside the body for long periods of time. If viable cysts are ingested, *Giardia* can cause the illness known as giardiasis, an intestinal illness that can cause nausea, anorexia, fever, and severe diarrhea. The symptoms last only for several days, and the body can naturally rid itself of the parasite in 1 to 2 months; however, for individuals with weakened immune systems, the

body often cannot rid itself of the parasite without medical treatment (CDC, 2015). In the United States, *Giardia* is the most commonly identified pathogen in waterborne disease outbreaks. Contamination of a water supply by *Giardia* can occur in two ways: (1) by the activity of animals in the watershed area of the water supply, or (2) by the introduction of sewage into the water supply. Wild and domestic animals are major contributors to the contamination of water supplies. Studies have also shown that, unlike many other pathogens, *Giardia* is not host specific. In short, *Giardia* cysts excreted by animals can infect and cause illness in humans. Additionally, in several major outbreaks of waterborne diseases, the *Giardia* cyst source was sewage-contaminated water supplies. Treating the water supply, however, can effectively control waterborne *Giardia*. Chlorine and ozone are examples of two disinfectants known to effectively kill *Giardia* cysts. Filtration of the water can also effectively trap and remove the parasite from the water supply. The combination of disinfection and filtration is the most effective water treatment process available today for prevention of *Giardia* contamination. In drinking water, *Giardia* is regulated under the Surface Water Treatment Rule. Although the SWTR does not establish a maximum contaminant level (MCL) for *Giardia*, it does specify treatment requirements to achieve at least 99.9% (3-log) removal or inactivation of *Giardia*. This regulation requires that all drinking water systems using surface water or groundwater under the influence of surface water must disinfect and filter the water. The Enhanced Surface Water Treatment Rule (ESWTR), which includes *Cryptosporidium* and further regulates *Giardia*, was established in 1996.

Giardiasis Giardiasis is recognized as one of the most frequently occurring waterborne diseases in the United States. *Giardia lamblia* cysts have been discovered in places as far apart as Estes Park, Colorado (near the Continental Divide); Missoula, Montana; Wilkes-Barre, Scranton, and Hazleton, Pennsylvania; and Pittsfield and Lawrence, Massachusetts, just to name a few. Giardiasis is characterized by intestinal symptoms that usually last a week or more and may be accompanied by one or more of the following: diarrhea, abdominal cramps, bloating, flatulence, fatigue, and weight loss. Although vomiting and fever are commonly listed as relatively frequent symptoms, people involved in waterborne outbreaks in the United States have not commonly reported them. Most *Giardia* infections persist only for 1 or 2 months, but some people experience a more chronic phase that can follow the acute phase or may become manifest without an antecedent acute illness. Loose stools and increased abdominal gassiness with cramping, flatulence, and burping characterize the chronic phase. Fever is not common, but malaise, fatigue, and depression may ensue; for a small number of people, the persistence of infection is associated with the development of marked malabsorption and weight loss (Weller, 1985). Similarly, lactose (milk) intolerance can be a problem for some people. This can develop coincidentally with the infection or be aggravated by it, causing an increase in intestinal symptoms after ingestion of milk products. Some people may have several of these symptoms without evidence of diarrhea or have only sporadic episodes of diarrhea every three or four days. Still others may have no symptoms at all. The problem, then, may not be one of determining whether or not someone is infected with the parasite but how harmoniously the host and the parasite can live together. When such harmony does not exist or is lost, it then becomes a problem of how to get rid of the parasite, either spontaneously or by treatment.

Three prescription drugs available in the United States to treat giardiasis are quinacrine, metronidazole, and furazolidone. In a paper comparing the effectiveness of these drugs in treating giardiasis, quinacrine was reported to have an efficacy of 90% or greater; metronidazole has an efficacy rate of 60 to 100%; and

furazolidone has an efficacy rate of 80 to 96% (Gardner and Hill, 2001). Quinacrine is generally the least expensive of the anti-Giardia medications, but it often causes vomiting in children younger than 5 years old. Although the treatment of giardiasis is not an FDA-approved indication for metronidazole, the drug is commonly used for this purpose. Furazolidone is considered to be the least effective of the three drugs but is the only anti-Giardia medication that comes in liquid preparation, which makes it easier to deliver the exact dose to small children who have difficulty taking pills. Giardiasis occurs worldwide. In the United States, Giardiasis is the parasite most commonly identified in stool specimens submitted to state laboratories for parasitologic examination. During a 3-year period, approximately 4% of 1 million stool specimens submitted to state laboratories tested positive for Giardiasis (CDC, 1979). Other surveys have demonstrated Giardiasis prevalence rates ranging from 1 to 20%, depending on the location and ages of persons studied. Giardiasis ranks among the top 20 infectious diseases that cause the greatest morbidity in Africa, Asia, and Latin America; about 200 million people in these regions have symptomatic infections (Feng and Xiao, 2011). People who are at highest risk for acquiring Giardiasis infection in the United States may be placed into five major categories:

1. People in cities whose drinking water originates from streams or rivers and whose water treatment process does not include filtration, or where filtration is ineffective because of malfunctioning equipment
2. Hikers, campers, and those who enjoy the outdoors
3. International travelers
4. Children who attend daycare centers, daycare center staff, and parents and siblings of children infected in daycare centers
5. Homosexual men

People in categories 1, 2, and 3 have in common the same general source of infection; that is, they acquire Giardiasis from fecally contaminated drinking water. City residents usually become infected because the municipal water treatment process does not include the filter necessary to physically remove the parasite from the water. The number of people in the United States at risk (i.e., the number who receive municipal drinking water from unfiltered surface water) is estimated to be 20 million. International travelers may also acquire the parasite from improperly treated municipal waters in cities or villages in other parts of the world, particularly in developing countries. In Eurasia, only travelers to Leningrad appear to be at increased risk. In prospective studies, 88% of U.S. and 35% of Finnish travelers to Leningrad who had negative stool tests for Giardiasis on departure to the Soviet Union developed symptoms of giardiasis and had positive tests for Giardiasis after they returned home (Brodsky et al., 1974). With the exception of visitors to Leningrad, however, Giardiasis has not been implicated as a major cause of traveler's diarrhea, as it has been detected in fewer than 2% of travelers who develop diarrhea. However, hikers and campers risk infection every time they drink untreated raw water from a stream or river. Persons in categories 4 and 5 become exposed through more direct contact with feces or an infected person—exposure to the soiled diapers of an infected child in cases associated with daycare centers or through direct or indirect anal–oral sexual practices in the case of homosexual men. Although community waterborne outbreaks of giardiasis

have received the greatest publicity in the United States during the past decade, about half of the *Giardia* cases discussed with staff of the Centers for Disease Control (CDC) over a 3-year period had a day-care center exposure as the most likely source of infection. Numerous outbreaks of *Giardia* in daycare centers have been reported. Infection rates for children in daycare center outbreaks have ranged from 21 to 44% in the United States and from 8 to 27% in Canada (Black et al., 1981; Keystone et al., 1978, 1984; Pickering et al., 1981, 1984; Sealy and Schuman, 1983). The highest infection rates are usually observed in children who wear diapers (1 to 3 years of age). In a CDC study of 18 randomly selected daycare centers in Atlanta, 10% of diapered children were found to be infected. Transmission from this age group to older children, daycare staff, and household contacts is also common. About 20% of parents caring for an infected child become infected. Local health officials and managers of water utility companies need to realize that sources of *Giardia* infection other than municipal drinking water exist. Armed with this knowledge, they are less likely to make a quick (and sometimes wrong) assumption that a cluster of recently diagnosed cases in a city is related to municipal drinking water. Of course, drinking water must not be ruled out as a source of infection when a larger than expected number of cases is recognized in a community, but the possibility that the cases are associated with a daycare center outbreak, drinking untreated stream water, or international travel should also be entertained. To understand the finer aspects of *Giardia* transmission and strategies for control, drinking water practitioners must become familiar with several aspects of the parasite's biology. Two forms of the parasite exist: a trophozoite and a cyst, both of which are much larger than bacteria (Figure 6.4). Trophozoites live in the upper small intestine, where they attach to the intestinal wall by means of a disc-shaped suction pad on their ventral surface. Trophozoites actively feed and reproduce at this location. At some time during the trophozoite's life, it releases its hold on the bowel wall and floats in the fecal stream through the intestine. As it makes this journey, it undergoes a morphologic transformation into an egg-like structure called a cyst. The cyst (about 6 to 9 μm in diameter and 8 to 12 μm in length) has a thick exterior wall that protects the parasite against the harsh elements that it will encounter outside the body. This cyst form of parasite is infectious to other people or animals. Most people become infected either directly (by hand-to-mouth transfer of cysts from the feces of an infected individual) or indirectly (by drinking feces-contaminated water). Less common modes of transmission include ingestion of fecally contaminated food and hand-to-mouth transfer of cysts after touching a fecally contaminated surface. After the cyst is swallowed, the trophozoite is liberated through the action of stomach acid and digestive enzymes and becomes established in the small intestine. Although infection after ingestion of only one *Giardia* cyst is theoretically possible, the minimum number of cysts shown to infect a human under experimental conditions is 10 (Rendroff, 1954). Trophozoites divide by binary fission about every 12 hours. What this means in practical terms is that if a person swallowed only a single cyst, reproduction at this rate would result in more than 1 million parasites 10 days later and 1 billion parasites by day 15. The exact mechanism by which *Giardia* causes illness is not well understood, but it is not necessarily related to the number of organisms present. Nearly all of the symptoms, however, are related to dysfunction of the gastrointestinal tract. The parasite rarely invades other parts of the body, such as the gall bladder or pancreatic ducts. Intestinal infection does not result in permanent damage. Data reported by the CDC indicate that *Giardia* is the most frequently identified cause of diarrheal outbreaks associated with drinking water in the United States. The remainder of this section is devoted specifically to waterborne transmissions of *Giardia*. *Giardia* cysts have been detected in 16% of potable water sup-

plies (lakes, reservoirs, rivers, springs, groundwater) in the United States at an average concentration of 3 cysts per 100 L (Rose et al., 1991). The CDC reported that 242 outbreaks occurred from 1972 to 2011 (Adam et al., 2016). In 1983, for example, *Giardia* was identified as the cause of diarrhea in 68% of waterborne outbreaks in which the causal agent was identified. In 1984, about 250,000 people in Pennsylvania were advised to boil their drinking water for 6 months because of *Giardia*-contaminated water. In 2007, an outbreak occurred in New Hampshire that caused illness in 31 people (Daly et al., 2010). Many of the municipal waterborne outbreaks of *Giardia* have been subjected to intense study to determine their cause. Several general conclusions can be made from data obtained in those studies. Waterborne transmission of *Giardia* in the United States usually occurs in mountainous regions where community drinking water obtained from clear running streams is chlorinated but not filtered before distribution. Although mountain streams appear to be clean, fecal contamination upstream by human residents or visitors, as well as by *Giardia*-infected animals such as beavers, has been well documented. Water obtained from deep wells is an unlikely source of *Giardia* because of the natural filtration of water as it percolates through the soil to reach underground cisterns. Wells that pose the greatest risk of fecal contamination are poorly constructed or improperly located ones. A few outbreaks have occurred in towns that include filtration in the water treatment process, but the filtration was not effective in removing *Giardia* cysts because of defects in filter construction, poor maintenance of the filter media, or inadequate pretreatment of the water before filtration. Occasional outbreaks have also occurred because of accidental cross-connections between water and sewage systems. Two major ingredients are necessary for a waterborne outbreak: (1) *Giardia* cysts must be present in untreated source water, and (2) the water purification process must fail to either kill or remove *Giardia* cysts from the water. Although beavers are often blamed for contaminating water with *Giardia* cysts, the fact that they are responsible for introducing the parasite into new areas seems unlikely. Far more likely is that they are also victims: *Giardia* cysts may be carried in untreated human sewage discharged into the water by small-town sewage disposal plants or they may originate from cabin toilets that drain directly into streams and rivers. Backpackers, campers, and sports enthusiasts may also deposit *Giardia*-contaminated feces in the environment, which are subsequently washed into streams by rain. In support of this concept is a growing amount of data indicating a higher *Giardia* infection rate in beavers living downstream from U.S. national forest campgrounds when compared with beavers living in more remote areas that have a near zero rate of infection. Although beavers may be unwitting victims of the *Giardia* story, they still play an important part in the contamination scheme, because they can (and probably do) serve as amplifying hosts. An amplifying host is one that is easy to infect, serves as a good habitat for the parasite to reproduce, and, in the case of *Giardia*, returns millions of cysts to the water for every one ingested. Beavers are especially important in this regard, because they tend to defecate in or very near the water, which ensures that most of the *Giardia* cysts excreted are returned to the water. The contribution of other animals to waterborne outbreaks of *Giardia* is less clear. Muskrats (another semiaquatic animal) have been found in several parts of the United States to have high infection rates (30 to 40%) (Frost et al., 1980). Studies have shown that muskrats can be infected with *Giardia* cysts from humans and beavers. Occasional *Giardia* infections have been reported in coyotes, deer, elk, cattle, dogs, and cats (but not in horses and sheep) encountered in mountainous regions of the United States. Naturally occurring *Giardia* infections have not been found in most other wild animals (e.g., bear, nutria, rabbit, squirrel, badger, marmot, skunk, ferret, porcupine, mink, raccoon, river otter, bobcat, lynx, moose, bighorn sheep). Knowledge

about what is required to kill or remove *Giardia* cysts from a contaminated water supply has increased considerably. For example, we know that cysts can survive in cold water (4°C) for at least 2 months, and they are killed instantaneously by boiling water (100°C) (Bingham et al., 1979). We do not know how long the cysts will remain viable at other water temperatures (e.g., at 0°C or in a canteen at 15 to 20°C), nor do we know how long the parasite will survive on various environment surfaces, such as under a pine tree, in the sun, on a diaper-changing table, or in carpets in a daycare center. Their survivability decreases as the temperature increases (USEPA, 2000). The effect of chemical disinfection (chlorine, for example) on the viability of *Giardia* cysts is an even more complex issue. The number of waterborne outbreaks of *Giardia* that have occurred in communities where chlorine was employed as a disinfectant demonstrates that the amount of chlorine used routinely for municipal water treatment is not effective against *Giardia* cysts. These observations were confirmed in the laboratory under experimental conditions (Jarroll et al., 1980a,b). This does not mean that chlorine does not work at all. It does work under certain favorable conditions. Without getting too technical, gaining some appreciation of the problem can be achieved by understanding a few of the variables that influence the efficacy of chlorine as a disinfectant:

- Water pH—At pH values above 7.5, the disinfectant capability of chlorine is greatly reduced.
- Water temperature—The warmer the water, the higher the efficacy. Chlorine does not work in ice-cold water from mountain streams.
- Organic content of the water—Mud, decayed vegetation, or other suspended organic debris in water chemically combines with chlorine, making it unavailable as a disinfectant.
- Chlorine contact time—The longer that *Giardia* cysts are exposed to chlorine, the more likely it is that the chemical will kill them.
- Chlorine concentration—The higher the chlorine concentration, the more likely it is that chlorine will kill *Giardia* cysts. Most water treatment facilities try to add enough chlorine to give a free (unbound) chlorine residual at the customer tap of 0.5 mg per liter of water.

These variables are so closely interrelated that improving one can often compensate for another; for example, if chlorine efficacy is expected to be low for icy stream water, the chlorine contact time or chlorine concentration, or both, could be increased. In the case of *Giardia*-contaminated water, producing safe drinking water with a chlorine concentration of 1 mg per liter and contact time as short as 10 minutes might be possible if all the other variables are optimal—a pH of 7.0, water temperature of 25°C, and total organic content of the water close to zero. On the other hand, if all of these variables are unfavorable—pH of 7.9, water temperature of 5°C, and high organic content—chlorine concentrations in excess of 8 mg/L with several hours of contact time may not be consistently effective. Because water conditions and water treatment plant operations (especially those related to water retention time and, therefore, to chlorine contact time) vary considerably in different parts of the United States, neither the USEPA nor the CDC has been able to identify a chlorine concentration that would be safe yet effective against *Giardia* cysts under all water conditions. For this reason, the use of chlorine as a preventive measure against waterborne giardiasis generally has been used under outbreak conditions when the amount of chlorine and contact time have been tailored to fit specific water conditions and the existing operational design of the water utility. In an outbreak, for example, the local health department and water utility may issue an advisory to boil water, may increase the chlorine residual at the consumer's tap from 0.5 mg/L to 1 or 2 mg/L, and, if the physical layout and operation of the water treatment facility permit, increase the chlorine contact time. These are emergency procedures intended to reduce the risk of transmission until a filtration device can be installed or repaired or until an alternative source of safe water (a well, for example) can be made op-

erational. The long-term solution to the problem of municipal waterborne outbreaks of giardiasis involves improvements in and more widespread use of filters in the municipal water treatment process. The sand filters most commonly used in municipal water treatment today cost millions of dollars to install, which makes them unattractive for many small communities. The pore sizes in these filters are not sufficiently small to remove Giardia (6 to 9 μm by 8 to 12 μm). For the sand filter to remove Giardia cysts from the water effectively, the water must receive some additional treatment before it reaches the filter. The flow of water through the filter bed must also be carefully regulated. An ideal prefilter treatment for muddy water would include sedimentation (a holding pond where large suspended particles are allowed to settle out by the action of gravity) followed by flocculation or coagulation (the addition of chemicals such as alum or ammonium to cause microscopic particles to clump together). The sand filter easily removes the large particles resulting from the flocculation–coagulation process, including Giardia cysts bound to other microparticulates. Chlorine is then added to kill the bacteria and viruses that may escape the filtration process. If the water comes from a relatively clear source, chlorine may be added to the water before it reaches the filter. The successful operation of a complete waterworks operation is a complex process that requires considerable training. Troubleshooting breakdowns or recognizing the potential problems in the system before they occur often requires the skills of an engineer. Unfortunately, most small water utilities with water treatment facilities that include filtration cannot afford the services of a full-time engineer. Filter operation or maintenance problems in such systems may not be detected until a Giardia outbreak is recognized in the community. The bottom line is that, although filtration is the best protection against waterborne giardiasis that water treatment technology has to offer for municipal water systems, it is not infallible. For municipal water filtration facilities to work properly, they must be properly constructed, operated, and maintained. Whenever possible, persons outdoors should carry drinking water of known purity with them. When this is not practical and when water from streams, lakes, ponds, or other outdoor sources must be used, time should be taken to properly disinfect the water before drinking it. Boiling water is one of the simplest and most effective ways to purify water. Boiling for one minute is adequate to kill Giardia as well as most other bacterial or viral pathogens likely to be acquired from drinking polluted water. Disinfecting water with chlorine or iodine is considered less reliable than boiling for killing Giardia; however, we recognize that boiling drinking water is not practical under many circumstances. When boiling drinking water is not possible, chemical disinfectants such as iodine or chlorine should be used. They offer some protection against Giardia and destroy most bacteria and viruses that cause illness. Iodine or chlorine concentrations of 8 mg/L (8 ppm) with a minimum contact time of 30 minutes are recommended. If the water is cold (less than 10°C or 50°F), a minimum contact time of 60 minutes is recommended. If a choice of disinfectants is available, use iodine. The disinfectant activity of iodine is less likely than that of chlorine to be reduced by unfavorable water conditions, such as dissolved organic material in the water or a high pH. Table 6.5 gives instructions for disinfecting water using household tincture of iodine, and Table 6.6 gives instructions for using chlorine bleach. If water is visibly dirty, it should first be strained through a clean cloth into a container to remove any sediment or floating matter. The water should then be treated with chemicals as shown in the tables. Portable filter devices for field or individual use as well as some household filters are available for use against waterborne giardiasis. Manufacturer data accompanying these filters indicate that some can remove particles the size of a Giardia cyst or smaller and may be capable of providing a source of safe drinking water for an individual or family during a waterborne outbreak. If

carefully selected, such devices might also be useful in preventing giardiasis for international travelers, backpackers, campers, sportsmen, or persons who live or work in areas where water is known to be contaminated. Unfortunately, very few published reports in the scientific literature detail both the methods used and the results of tests employed to evaluate the efficacy of these filters against *Giardia*. Until more published experimental data become available, consumers should look for a few common-sense indications when selecting a portable or household filter. The first thing to consider is the filter media. Filters relying solely on ordinary or silver-impregnated carbon or charcoal should be avoided, because they are not intended to prevent, destroy, or repel microorganisms. Their principal use is to remove undesirable chemicals, odors, and very large particles such as rust or dirt. Some filters rely on chemicals such as iodide-impregnated resins to kill *Giardia*. Although properly designed and manufactured iodide-impregnated resin filters have been shown to kill many species of bacteria and viruses present in human feces, their efficacy against *Giardia* cysts is less well established. The principle under which these filters operate is similar to that achieved by adding the chemical disinfectant iodine to water, except that the microorganisms in the water pass over the iodide-impregnated disinfectant as the water flows through the filter. The disinfectant activity of iodide is not as readily affected as chlorine by water pH or organic content, but iodide disinfectant activity is markedly reduced by cold water temperatures. Experiments on *Giardia* indicate that many of the cysts in cold water (4°C) remain viable after passage through filters containing triiodide or pentaiodide disinfectant (Marchin et al., 1983). Longer contact time (compared to those required to kill bacteria) is required when using chemical filters to process cold water for *Giardia* protection. Currently available chemical filters are also not recommended for muddy or very turbid water. Note that filters relying solely on chemical action usually give no indication to the user when disinfectant activity has been depleted. The so-called microstrainer types of filters are true filters. Manufacturer data accompanying these filters indicate that some have a sufficiently small pore size to physically restrict the passage of some microorganisms through the filter. The types of filter media employed in microstraining filters include acrylic, ceramic, and proprietary materials. Theoretically, a filter having an absolute pore size of less than 6 µm might be able to prevent *Giardia* cysts 8 to 10 µm in diameter from passing through. When used as a water sampling device during community outbreaks, portable filters in the 1 to 3-µm range more effectively removed *Giardia* cysts from raw water than filters with larger pore sizes. For effective removal of bacterial or viral organisms that cause disease in humans, microstraining filters with pore sizes of less than 1 µm are advisable; however, the smaller the pores, the more quickly the filters will tend to clog. To obtain maximum filter life, and as a matter of reasonable precaution, the cleanest available water source should always be used. Keep in mind, however, that even sparkling, clear mountain streams can be heavily contaminated. Another thing to consider when choosing a filter includes whether the filter element can be cleaned or replaced without posing a significant health hazard to the user, because infectious organisms can be concentrated on the filter element or media. Properly engineered portable filters should minimize the possibility of contaminating the clean water side of the filter with contaminated water during replacement or cleaning of the filter element. Because filters used in the field are often rinsed in a stream or river that may be contaminated, this is an especially important consideration for recreational outdoor use.

Cryptosporidium In 1907, when Ernest E. Tyzzer recognized, described, and published an account of a parasite he frequently found in the gastric glands of laboratory mice, he and his new discovery were overlooked—just another scientist going quietly about his normal, tedious, out-of-the-limelight research, buried in ob-

curity. Initially, his studies focused on describing the asexual and sexual stages and spores (oocysts), each with a specialized attachment organelle, and he noted that the spores were excreted in the feces. Tyzzer identified the parasite as a sporozoan, but of uncertain taxonomic status; he named it *Cryptosporidium muris* (Tyzzer, 1907). Later, in 1910, after more detailed study, he proposed *Cryptosporidium* as a new genus and *C. muris* as the type species. Amazingly, except for developmental stages, Tyzzer's original description of the life cycle (see Figure 6.5) was later confirmed by electron microscopy. Then, in 1912, Tyzzer described a new species, *Cryptosporidium parvum*. For almost 50 years, Tyzzer's discovery of the genus *Cryptosporidium* remained (like himself) relatively obscure because it appeared to be of no medical or economic importance. Slight rumblings of the importance of the genus began to be felt in the medical community when Slavin (1955) wrote about a new species, *Cryptosporidium melagridis*, which was associated with illness and death in turkeys. Interest remained slight even when *Cryptosporidium* was found to be associated with bovine diarrhea (Panciera et al., 1971). Not until 1982 did worldwide interest focus on the study of organisms in the genus *Cryptosporidium*. At that time, the medical community and other interested parties were beginning a full-scale, frantic effort to find out as much as possible about acquired immune deficiency syndrome (AIDS), and the CDC reported that 21 AIDS-infected males from six large cities in the United States had severe protracted diarrhea caused by *Cryptosporidium*. It was in 1993, though, that *Cryptosporidium*—the “pernicious parasite”—made itself and Milwaukee famous (Mayo Foundation, 1996). The massive waterborne outbreak in Milwaukee, Wisconsin, where more than 400,000 persons developed acute and often prolonged diarrhea or other gastrointestinal symptoms, increased awareness of *Cryptosporidium* at an exponential level. The Milwaukee incident spurred both public interest and the interest of public health agencies, agricultural and environmental agencies and groups, and suppliers of drinking water. This increase in interest level and concern spurred new studies of *Cryptosporidium* with an emphasis on developing methods for recovery, detection, prevention, and treatment (Fayer et al., 1997). The USEPA became particularly interested in this “new” pathogen; for example, in their reexamination of water treatment and disinfection regulations, the USEPA issued maximum contaminant level goals (MCLGs) for *Cryptosporidium* and added it to their Contaminant Candidate Lists (CCLs). Its similarity to *Giardia lamblia* and the necessity to provide an efficient conventional water treatment capable of eliminating viruses forced the USEPA to regulate surface water supplies in particular. The Enhanced Surface Water Treatment Rule (ESWTR), promulgated in 1998, includes regulations covering watershed protection, specialized operation of treatment plants (certification of operators and state overview), and effective chlorination. Protection against *Cryptosporidium* includes control of waterborne pathogens such as *Giardia* and viruses (DeZuane, 1997).

Cryptosporidium Basics *Cryptosporidium* is one of several single-celled protozoan genera in the phylum Apicomplexa (all referred to as coccidian). *Cryptosporidium* along with other genera in the phylum Apicomplexa develop in the gastrointestinal tract of vertebrates through all of their life cycle; in short, they live in the intestines of animals and people. This microscopic pathogen causes a disease called cryptosporidiosis. The dormant (inactive) form of *Cryptosporidium* is called an oocyst and is excreted in the feces of infected humans and animals. The tough-walled oocysts survive under a wide range of environmental conditions (Kneen et al., 2004). Several species of *Cryptosporidium* incorrectly named after the host in which they were found have been invalidated, but today at least 26 species of *Cryptosporidium* are recognized as valid (Ryan et al., 2014); eight of these are listed in (Table 6.7). *C. muris* infects the gastric glands of

laboratory rodents and several other mammalian species but is not known to infect humans (even though several texts state otherwise). *C. parvum*, however, infects the small intestine of an unusually wide range of mammals, including humans, and is the zoonotic species responsible for human cryptosporidiosis. In most mammals, *C. parvum* is predominately a parasite of neonate (newborn) animals. Even though exceptions occur, older animals generally develop poor infections, even when unexposed previously to the parasite (Upton, 1997). Humans are the one host that can be seriously infected at any time in their lives, and only previous exposure to the parasite results in either full or partial immunity to challenge infections (Upton, 1997). Oocysts are present in most surface bodies of water across the United States, many of which supply public drinking water. Oocysts are more prevalent in surface waters when heavy rains increase runoff of wild and domestic animal wastes from the land or when sewage treatment plants are overloaded or break down. Only laboratories with specialized capabilities can detect the presence of *Cryptosporidium* oocysts in water. Unfortunately, current sampling and detection methods are unreliable. Recovering oocysts trapped on the material used to filter water samples is difficult. When a sample has been obtained, however, determining whether the oocyst is alive and if it is *C. parvum* and thus can infect humans can be easily accomplished by looking at the sample under a microscope. The number of oocysts detected in raw (untreated) water varies with location, sampling time, and laboratory methods. Water treatment plants remove most, but not always all, oocysts. Low numbers of oocysts are sufficient to cause cryptosporidiosis, but the low numbers of oocysts sometimes present in drinking water are not considered cause for alarm for the public. Protecting water supplies from *Cryptosporidium* demands multiple barriers. Why? Because *Cryptosporidium* oocysts have tough walls that can withstand many environmental stresses and are resistant to chemical disinfectants such as chlorine that are traditionally used in municipal drinking water systems and swimming pools. Physical removal of particles, including oocysts, from water by filtration is an important step in the water treatment process. Typically, water pumped from rivers or lakes into a treatment plant is mixed with coagulants (see Chapter 11), which help settle out particles suspended in the water. If sand filtration is used, even more particles are removed. Finally, the clarified water is disinfected and piped to customers. Filtration is the only conventional method now in use in the United States for controlling *Cryptosporidium*. Ozone is a strong disinfectant (see Chapter 11) that kills protozoa if sufficient doses and contact times are used, but ozone leaves no residual for killing microorganisms in the distribution system, as does chlorine. The high costs of new filtration or ozone treatment plants must be weighed against the benefits of additional treatment. Even well-operated water treatment plants cannot ensure that drinking water will be completely free of *Cryptosporidium* oocysts. Water treatment methods alone cannot solve the problem; watershed protection and monitoring of water quality are critical. Land use controls such as septic system regulations and best management practices to control runoff can help keep human and animal wastes out of water. Under the Surface Water Treatment Rule of 1989, public water systems must filter surface water sources unless water quality and disinfection requirements are met and a watershed control program is maintained. This rule, however, did not address *Cryptosporidium*. The USEPA has now set standards for turbidity (cloudiness) and coliform bacteria (which indicate that pathogens are probably present) in drinking water. Frequent monitoring must occur to provide officials with early warning of potential problems to enable them to take steps to protect public health. Unfortunately, no water quality indicators can reliably predict the occurrence of cryptosporidiosis. More accurate and rapid assays of oocysts will make it possible to notify residents promptly if their water supply is con-

taminated with *Cryptosporidium* and thus avert outbreaks. The bottom line is that the collaborative efforts of water utilities, government agencies, healthcare providers, and individuals are needed to prevent outbreaks of cryptosporidiosis.

SIDEBAR: SYDNEY AUSTRALIA* From the end of July to the end of September 1998, upon three occasions, residents of the city of Sydney, Australia, had to take the precaution of boiling their drinking water. Testing found *Giardia* and *Cryptosporidium* in the public water supply. According to the Sydney authorities, at these levels the *Giardia* and *Cryptosporidium* cysts posed little, if any, health threat. No incidents of illness were linked to the presence of *Giardia* and *Cryptosporidium*; however, businesses that relied on large quantities of pure water could not function on a boil-alert quality of water. Evidence seemed to indicate that the plant itself was creating the problem and that the results of water tests performed by the lab (Australian Water Technologies) were either conducted improperly or were not read properly and misinterpreted. The aftermath of the incidents left the Sydney Water Corporation, the privately owned organization handling the treatment systems since privatization in 1995, in shambles. Beginning on July 29, 1998, the three boil alerts led to a massive investigation into the causes and sources of the contamination, as well as the resignation of the Sydney Water Corporation's managing director and chairman, whose blossoming political career was cut short. Sydney Water Corporation was stripped of responsibility and its major assets; it lost all control of its treatment plants, dams, and catchment to the government's new Sydney Catchment Authority. Sydney Water Corporation was ordered to repay residential water users for the expense and trouble of using bottled water, and, of course, numerous lawsuits were initiated by businesses and industries affected by the shutdown. On the positive side, Australia has put an American-style Clean Water Act into place (which, if nothing else, will establish guidelines to follow in such a case), and Sydney is working to ensure good preventive maintenance measures for watershed protection. Of special interest to water pollution control technologists are the tests, their results, and the difficulty in pinpointing the source (or sources) and cause of the contamination. Experts warned that actually finding the direct source of the Sydney outbreaks was unlikely (e.g., the cause of the 1995 outbreak in Milwaukee is uncertain), and they recommended installing either an ozonation or microfiltration system to ensure completely safe drinking water. Such expert advice, though, presumed actual *Giardia* and *Cryptosporidium* contamination—which at that point was in more than a little doubt. Test results on the same water samples taken during the outbreaks varied widely. Tests for the later shutdowns were less accurate than ones for the initial shutdown—not surprising under the panic conditions at the lab, which was under tremendous pressure to find the causes and was reluctant to risk either consumer wrath over the inconvenience or consumer illness and death due to contamination. One test sample was read at 1000 *Cryptosporidium* oocysts initially, but a reexamination of the sample found only 2 oocysts. Technicians may also have mistaken harmless algae similar in appearance to *Giardia* and *Cryptosporidium* for the dangerous cysts, raising false (and expensive) alarms. Even in retesting, test results were shaky. The New South Wales Health Department counted what they thought were more than 9000 oocysts per 100 liters of treated water for one sample—higher levels than testing should find in raw sewage. An expert from the department of civil engineering at the University of New South Wales who saw lots of different algae and no *Cryptosporidium* in his own tests on the water pointed out that the highest U.S. level ever reported was 1000—and that those U.S. reports included the 1995 Milwaukee outbreak, where hundreds of thousands of people fell ill. He also pointed out that other common fecal bacteria should be present in the sample as well, but were

not (Anon., 1998). The moral of the story? Know your stuff. Be sure of your technique and do everything you can to ensure the accuracy of your samples and test results. As a water control technologist, you may have to turn in test results that open a similar can of worms at some point—or announce unsafe water supplies to the press. **Cryptosporidiosis** *Cryptosporidium parvum* is an important emerging pathogen in the U.S. and a cause of severe, life-threatening disease in patients with AIDS. No safe and effective form of specific treatment for cryptosporidiosis has been identified to date. The parasite is transmitted by ingestion of oocysts excreted in the feces of infected humans or animals. The infection can therefore be transmitted from person-to-person, through ingestion of contaminated water (drinking water and water used for recreational purposes) or food, from animal to person, or by contact with fecally contaminated environmental surfaces. Outbreaks associated with all of these modes of transmission have been documented. Patients with human immunodeficiency virus infection should be made more aware of the many ways that *Cryptosporidium* species are transmitted, and they should be given guidance on how to reduce their risk of exposure. Juranek (1995) Since the Milwaukee outbreak, concern about the safety of drinking water in the United States has increased, and new attention has been focused on determining and reducing the risk of acquiring cryptosporidiosis from community and municipal water supplies. Cryptosporidiosis is spread by putting something in the mouth that has been contaminated with the stool of an infected person or animal. In this

way, people swallow the *Cryptosporidium* parasite. As mentioned earlier, a person can become infected by drinking contaminated water or eating raw or undercooked food contaminated with *Cryptosporidium* oocysts, by direct contact with the droppings of infected animals or stools of infected humans, or by hand-to-mouth transfer of oocysts from surfaces that may have become contaminated with microscopic amounts of stool from an infected person or animal. Symptoms may appear 2 to 10 days after infection by the parasite. Although some persons may not have symptoms, others have watery diarrhea, headache, abdominal cramps, nausea, vomiting, and low-grade fever. These symptoms may lead to weight loss and dehydration. In otherwise healthy persons, these symptoms usually last 1 to 2 weeks, at which time the immune system is able to defeat the infection. In persons with suppressed immune systems, such as persons who have AIDS or who recently have had an organ or bone marrow transplant, the infection may continue and become life threatening. Currently, no safe and effective cure for cryptosporidiosis exists. People with normal immune systems improve without taking antibiotic or antiparasitic medications. The treatment recommended for this diarrheal illness is to drink plenty of fluids and to get extra rest. Physicians may prescribe medication to slow the diarrhea during recovery. The best way to prevent cryptosporidiosis is to

- Avoid water or food that may be contaminated.
- Wash hands after using the toilet and before handling food.
- Be sure, if you work in a daycare center, to wash your hands thoroughly with plenty of soap and warm water after every diaper change, even if you wear gloves when changing diapers.

During community-wide outbreaks caused by contaminated drinking water, drinking water practitioners should inform the public to boil drinking water for 1 minute to kill the *Cryptosporidium* parasite.

Cyclospora *Cyclospora* organisms, which until recently were considered blue-green algae, were discovered at the turn of the century. The first human cases of *Cyclospora* infection were reported in the 1970s. In the early 1980s, *Cyclospora* was recognized as a pathogen in patients with AIDS. We now know that *Cyclospora* is endemic in many parts of the world and appears to be an important cause of traveler's diarrhea. *Cyclospora* are two to three times larger than *Cryptosporidium*, but otherwise have similar features.

Cyclospora diarrheal illness in patients with healthy immune systems can be cured with a week of therapy with trimethoprim–sulfamethoxazole (TMP–SMX). What is believed to be the first known outbreak of diarrheal illness associated with Cyclospora in the United States occurred in 1990 (Huang et al., 1995) and consisted of 21 cases of illness among physicians and others working at a Chicago hospital. Contaminated tap water from a physicians' dormitory at the hospital was the probable source of the organism. The tap water probably picked up the organism while in a storage tank at the top of the dormitory after the failure of a water pump.

Watery diarrhea, abdominal cramping, low-grade fever, and decreased appetite are common features of the illness. The illness also is marked by periods of remission and relapse that may continue for up to several weeks. Microscopic examination of stool specimens from 11 infected people showed many spherical bodies 8 to 10 μm in diameter that were identified as a Cyclospora species. The only other outbreaks associated with Cyclospora in the literature have been seasonal outbreaks in Nepal. One outbreak in Nepal was associated with chlorinated drinking water.

Cyclospora Basics Cyclospora cayetanensis is a unicellular parasite previously known as a cyanobacterium-like (blue–green algae-like) or coccidia-like body (CLB). Since the first known cases of illness caused by Cyclospora infection were reported in the medical journals in the 1970s, cases have been reported with increased frequency from around the world, in part because of the availability of better techniques for detecting the parasite in stool specimens. The transmission of Cyclospora is not a straightforward process. When infected persons excrete the oocyst state of Cyclospora in their feces, the oocysts are not infectious and may require from days to weeks to become infectious (i.e., to sporulate). Transmission of Cyclospora directly from an infected person to someone else is unlikely; however, indirect transmission can occur if an infected person contaminates the environment and oocysts have sufficient time, under appropriate conditions, to become infectious. Cyclospora, for example, may be transmitted by ingestion of water or food contaminated with oocysts. Outbreaks linked to contaminated water, as well as outbreaks linked to various types of fresh produce, have been reported (CDC, 1997a,b, 2016a; Herwaldt et al., 1997; Huang et al., 1995). How common the various modes of transmission and sources of infection are is not yet known, nor is it known whether animals can be infected and serve as sources of infection for humans. Persons of all ages are at risk for infection. Persons living or traveling in developing countries may be at increased risk, but infection can be acquired worldwide, including in the United States. In some countries of the world, infection appears to be seasonal. The incubation period between acquisition of infection and the onset of symptoms averages a week. Cyclospora infects the small intestine and typically causes watery diarrhea, with frequent, sometimes explosive stools. Other symptoms can include loss of appetite, substantial loss of weight, bloating, increased flatulence, stomach cramps, nausea, vomiting, muscle aches, low-grade fever, and fatigue. If untreated, illness may last for a few days to a month or longer and may follow a remitting–relapsing course. Some infected persons are asymptomatic. Identification of this parasite in stool requires special, not routine, laboratory tests to be done (discussed later). A single negative stool specimen does not rule out the diagnosis; three or more specimens may be required. Stool specimens should also be checked for other microbes that can cause a similar illness. TMP–SMX has been shown to be effective treatment for Cyclospora infection (CDC, 2016b). No alternative antibiotic regimen has been identified yet for patients who do not respond to or are intolerant of TMP–SMX. Based on currently available information, avoiding food or water that may be contaminated with stool is the best way to prevent

infection, and reinfection can occur.

Following are key points for the diagnosis of *Cyclospora* (Huang et al., 1995):

1. To maximize recovery of *Cyclospora* oocysts, first concentrate the stool specimen by the Formalin-ethyl acetate technique (centrifuge for 10 minutes at 500× g) and then examine a wet mount and/or stained slide of the sediment.
2. *Cyclospora* oocysts are 8 to 10 µm in diameter (in contrast, *Cryptosporidium parvum* oocysts are 4 to 6 µm in diameter).
3. Ultraviolet epifluorescence microscopy is a sensitive technique for rapidly examining stool sediments for *Cyclospora* oocysts, which autofluoresce (*Cryptosporidium parvum* oocysts do not). If suspect oocysts are found, bright-field microscopy can then be used to confirm that the structures have the characteristic morphologic features of *Cyclospora* oocysts (nonrefractile spheres that contain undifferentiated cytoplasm of refractile globules).
4. On a modified acid-fast-stained slide of stool (technique used by most laboratories), *Cyclospora* oocysts are variably acid fast (i.e., in the same field, oocysts may be unstained or stained from light pink to deep red). Unstained oocysts may have a wrinkled appearance; observers must distinguish oocysts from artifacts that may be acid fast but do not have the all-important wrinkled morphology of the oocyst wall.
5. Using a modified safranin technique, oocysts uniformly stain a brilliant reddish orange if fecal smears are heated in a microwave oven during staining (Visvesvara et al., 1997). If epifluorescence microscopy is available, the stained slide can first be examined with this technique and suspect oocysts reexamined with bright-field microscopy.
6. Although not recommended as an optimal technique for detection of *Cyclospora*, on a trichrome-stained slide of stool the oocysts appear as clear, round, and somewhat wrinkled.

HELMINTHS Drinking water in the United States may transmit the following intestinal worms (nematodes) (NAS, 1977):

- *Ascaris lumbricoides* (stomach worm) • *Trichuris trichiura* (whip worm) • *Ancylostoma duodenale* (hookworm) • *Necator americanus* (hookworm) • *Strongyloides stercoralis* (threadworm)

Along with inhabiting organic mud, worms also inhabit biological slimes and are derived from sewage and wet soil. Nematodes multiply in wastewater treatment plants; strict aerobes, they have been found in activated sludge and particularly in trickling filters and therefore appear in large concentrations in treated domestic liquid waste. Nematodes range in length from 0.5 to 3 mm and in diameter from 0.01 to 0.05 mm. Most species have a similar appearance. They have a body that is covered by cuticle, is cylindrical and nonsegmented, and tapers at both ends.

Nematodes ingest bacterial pathogens that protect them from water supply disinfectants and enhance their chances of reaching the consumer. Active motile nematode larvae can penetrate sand filters and survive chlorination, but they are not normally expected to cause parasitic nematode infections (NAS, 1977). Free-living nematodes have a life cycle consisting of egg, four larval stages, and one adult stage. Eggs are

easily recognizable in finished water, but raw water must have excessive microfaunal forms to allow identification. Environmental conditions have an impact on the growth of nematodes; for example, in anoxic conditions, their swimming and growth are impaired. Temperature fluctuations directly affect their growth and survival; nematode populations decrease when temperatures increase. Aquatic flatworms (improperly named because they are not all flat) feed primarily on algae. Because of their aversion to light, they are found in the lower depths of pools. Flatworms are very hardy and can survive in wide variations in humidity and temperature. Surface waters that are grossly polluted with organic matter (especially domestic sewage) have a fauna capable of thriving in very low concentrations of oxygen. A few species of tubificid worms dominate this environment. The bottoms of severely polluted streams can be literally covered with a “writhing mass” of these tubificids (Pennak, 1989). For the drinking water practitioner interested in learning more about aquatic worms, the current Standard Methods and Procedures has a section covering nematological examinations that details sample collection and provides an illustrated key to freshwater nematodes.

SUMMARY Pathogenic parasites are not easily removed or eliminated completely by conventional treatment and disinfection unit processes (DeZuane, 1997). This is particularly true for *Giardia lamblia*, *Cryptosporidium*, and *Cyclospora*. Filtration facilities can be adjusted in depth, prechlorination, filtration rate, and backwashing to become more effective in the removal of cysts. The pretreatment of protected watershed raw water is a major factor in the elimination of pathogenic protozoa (see Chapter 11). Before discussing the physical characteristics relevant to drinking water evaluation and the analysis of water found in nature as potential or actual sources of water supplies, some physical characteristics of water that are perhaps not so obvious should be mentioned. The sections that follow address the typical, traditional physical parameters of taste and odor, color, temperature, turbidity, and solids, but, as shown in Figure 7.1, this chapter also includes discussion about pH and solubility. Alkalinity and hardness are compared, even though they can also be considered chemical parameters. Finally, because of the importance of pH in water treatment, this chapter reviews the basic concepts of water solubility. It is important to point out that when this text refers to water quality the definition is predicated on the intended use of the water (in this case, potable use). Over the years, many parameters have evolved that qualitatively reflect the impact that various contaminants (impurities) have on water used for potable purposes; the following sections provide a brief discussion of these parameters. Before we discuss the parameters shown in Figure 7.1 let’s talk about where many of the physical contaminants come from. Think about hiking in a high mountain meadow and later waking from the miles-deep sleep of earned exhaustion to the awareness of peace . . . inhaling deep draughts of cool, clean mountain air; breathing through nostrils tickled with the pungency of pure, sweet pine . . . eardrums soothed by the light tattoo of fresh rain pattering against taut nylon . . . watching darkness lifted, then suddenly replaced with cloud-filtered daylight . . . being spellbound by the sudden, ordinary miracle of a new morning . . . anticipating expected adventures and appreciating the pure, unadulterated treasure of pristine wilderness momentarily owned, with minds not weighed down by mundane, everyday existence. Glorious account, isn’t it? Makes us want to pack up and head for the hills, so to speak. But there is one short phrase in the account that must be repeated here for emphasis: “eardrums soothed by the light tattoo of fresh rain pattering against taut nylon.” Rainfall is a key element of the natural water cycle, which is essential to maintaining life on Earth as we know it. But, there is more to rainfall than the sound of it striking against the taut nylon of a tent in the woods, or anywhere

else for that matter. Rainfall events are double-edged swords. They are one of the most important natural occurrences that life on this planet depends on, but they are also one of the most significant contributors to the degradation of drinking water source water quality affecting surface waters and groundwaters. Rainfall drives the movement of materials, including pathogens, into and through water bodies. It can move soil, resuspend sediments, cause overflow of combined and poorly maintained sewers, and degrade groundwater by infiltrating subsurface aquifers.

TASTE AND ODOR Under the Safe Drinking Water Act (SDWA), the U.S. Environmental Protection Agency (USEPA) issued guidelines to the states regarding secondary drinking water regulations. These guidelines apply to drinking water contaminants that may adversely affect the aesthetic qualities of water such as odor and appearance. Because these aesthetic qualities have no known adverse health effects, secondary regulations are not mandatory, but most drinking water systems comply with the limits. They have learned through experience that, although the odor and appearance of drinking water are not problems until a customer complains, one thing is certain—they will complain, and complain quite often. Disinfection itself often becomes a major source of complaint. Probably the most often expressed complaint among drinking water consumers is a “chlorine taste,” although the odor threshold can be as low as 0.2 to 0.4 mg/L at the typical pH level (DeZuane, 1997). Taste and odor are used jointly in the vernacular of water science. Even though drinking water taste and odor are not normally a problem until a consumer complains, drinking water practitioners have learned through experience that such problems may be an early indication of a potential health hazard. Taste and odor are important for aesthetic reasons (as a measure of the acceptability of water) and rarely have an impact on how safe water is to drink, but they should not be ignored. Objectionable taste and odor are more likely found at the raw water source than at the consumer’s tap. In general, water contaminants are attributable to contact with nature or human use. Taste and odor in water are caused by a variety of substances, including minerals, metals and salts from the soil, constituents of wastewater, and end products produced in biological reactions. Earthy or musty odors common in some water supplies are normally derived from natural biological processes. More offensive odors, such as those caused by hydrogen sulfide gas (H_2S), are not unusual in water supplies. The rotten-egg smell of hydrogen sulfide gas may be encountered in water that has been in contact with naturally occurring deposits of decaying organic matter. Groundwater supplies sometimes have this problem; such wells are commonly referred to as sulfur wells. Problems with tastes and odors are usually associated with surface rather than groundwater. Surface water taste and odor problems are normally caused by algae and other microorganisms, whereas groundwater taste and odor problems are generally the result of human interference or influence (e.g., landfill leachate). Note: The ability of humans to detect odor thresholds of various substances in water ranges from a low of about 1 $\mu\text{g/L}$ for methylisoborneol to a high of about 20 mg/L for chloroform. For testing performed in laboratories, consult Standard Methods for the Examination of Water and Wastewater (APHA-AWWA-WEF, 2017). The qualitative terms used to describe taste and odor are often classified as grassy, swampy, septic, musty, fishy, phenolic, and sweet. In water treatment, one of the common methods used to remove taste and odor is to use oxidants, including potassium permanganate and chlorine, to oxidize the materials causing the problem. Another common treatment method is to feed powdered activated carbon prior to the filter. The activated carbon has numerous small openings that adsorb the components that cause the odor and tastes. Taste and odor problems are also often controlled by watershed management, algicides, aeration, and pretreatment. Properly

functioning water filtration systems help to minimize taste and odor problems, as well. Odor is typically measured and expressed in terms of a threshold odor number (TON), which represents the dilution required to make the odor become virtually unnoticeable. In 1989, the USEPA issued a secondary maximum contaminant level (SMCL) of 3 TON for odor. (Remember that secondary standards apply to parameters not related to health.) When a dilution is used, a number can be derived to describe clarifying odor:

$$\text{Threshold odor number} = (VT + VD)/VT \quad (7.1)$$

where VT = volume tested, and VD = volume of dilution with odor-free distilled water. For VD = 0, TON = 1 (lowest value possible); for VD = VT, TON = 2; for VD = 2VT, TON = 3, etc. Note: Although taste and odor (along with color) are seldom connected to toxicological effects, the drinking water practitioner should never be fooled into assuming that a water supply with a “bit” of taste and odor will not offend the consumer. It will.

COLOR The quality of water can also be judged by its color, and the consumer does so, at least from a psychological point of view. Imagine going to the kitchen tap and drawing a glass of water that is rust colored, maybe to the point where you cannot even see your fingers on the other side of the glass. The rust-colored water may be safe to drink, but do you honestly think that the average consumer—who is used to drinking a colorless glass of water—is going to happily consume the rust-colored contents of that glass? Doubtful, at best. And let us not forget the folks in Flint, Michigan, who were provided tap water containing lead and other corrosion products sloughed off from aging pipes. Pure water is colorless, but water in nature is often colored by foreign substances, including organic matter from soils, vegetation, minerals, and aquatic organisms that are often present in natural waters. Color can also be contributed by municipal and industrial wastes. Color in water is classified as either true color or apparent color. Color partly due to dissolved solids that remain after removal of suspended matter is known as true color; color contributed by suspended matter is the apparent color. In water treatment, true color is the most difficult to remove. Color in water, although not usually considered unsafe or unsanitary, does present a treatment problem because it exerts a chlorine demand, which reduces the effectiveness of chlorine as a disinfectant. Color is measured by comparing the water sample with standard color solutions or colored glass disks. One color unit (CU) is equivalent to the color produced by a 1-mg/L solution of platinum. In 1989, the USEPA issued a secondary MCL of 15 color units for color. At 10 to 15 color units, color may not be visually detectable; at 100 color units, water may have the appearance of tea. Note: In practice, the process of isolating and identifying specific chemicals that cause the color is not practical. As we have pointed out, color in water is a matter of aesthetics; consumers do not find it acceptable. No matter how safe the water may be to drink, most people object strongly to water that offends their sense of sight. Given a choice, the public obviously would prefer clear, uncolored water. The effects of color in water, though, extend beyond psychological implications; for example, colored water affects laundering, papermaking, manufacturing, textiles, and food processing. The color of water has a profound effect on its marketability for both domestic and industrial use.

TEMPERATURE Water possesses many important thermal qualities; for example, water has a high specific heat. Water is not subject to rapid temperature fluctuations, because it can absorb or lose large amounts of heat with relatively small changes in temperature. Water temperature changes gradually in response to seasonal changes. Small water bodies will be influenced by air temperature more quickly than larger wa-

ter bodies. The ideal water supply has, at all times, an almost constant temperature or one with minimum variation. Real-world conditions, however, do not always provide this condition, especially in surface water supplies. Thermal pollution is often cited as

a cause of wild variations in surface water supplies (see Chapter 10). Many thermal pollution problems are a result of anthropogenic (human) activities; however, some water quality problems occur because of natural temperature fluctuations. Whatever the cause of temperature fluctuations, to live and reproduce fish and other aquatic organisms require certain conditions of temperature. The optimum temperature for trout (a coldwater fish) is 15°C, whereas carp require a temperature of about 32°C, more than twice the preferred temperature for trout. The problem with varying temperatures in surface waters (besides the impact on the health of the fish population) is that temperature affects the solubility of oxygen in water, the rate of bacterial activity, and the rate at which gases are transferred to and from the water, all of which are concerns for the drinking water practitioner. Water temperature also affects how efficiently certain water treatment processes operate; for example, temperature affects the rate at which chemicals dissolve and react. Cold water requires more chemicals for efficient coagulation and flocculation to take place. When water temperature is high, chlorine demand may rise due to the increased reactivity, and warmer temperatures often result in an increased level of algae and other organic matter in raw water. Temperature values are not normally standardized by public health criteria because of the insignificant health effects of water temperature. Water temperature, however, does have an influence on the treatment of water supplies, on the aquatic life of water reservoirs (biochemical reactions may double the reaction rate for a 10°C increase in temperature), on the taste of drinking water, on the level of dissolved oxygen, on the activity of organisms producing bad taste and odor, on the solubility of solids in water, and on the rate of corrosion of the distribution system (DeZuane, 1997). Note: When sampling, temperature readings must be done immediately because of changes caused by air temperature and manipulation of the sample.

TURBIDITY Turbidity is a unit of measurement quantifying the degree to which light traveling through a water column is scattered by the suspended organic (including algae) and inorganic particles. The scattering of light increases with a greater suspended load. Turbidity is commonly measured in nephelometric turbidity units (NTUs) but may also be measured in Jackson turbidity units (JTUs). Note: To obtain nephelometric turbidity units, observers compare the light scattered by the sample and the light scattered by a reference solution: Detection limits—Should be able to detect turbidity differences of 0.02 NTU with a range of 0 to 40 NTU Interferences—Rapidly settling coarse debris, dirty glassware, presence of air bubbles, and surface vibrations The velocity of the water resource largely determines the composition of the suspended load. Suspended loads are carried in both the gentle currents of lentic (lake) waters and the fast currents of lotic (flowing) waters. Even in flowing water, the suspended load usually consists of grains less than 0.5 mm in diameter. Suspended loads in lentic waters usually consist of the smallest sediment fractions—silt and clay.

Turbidity plays an important role in drinking water quality, for, without a doubt, one of the first things consumers notice about water is its clarity. Turbidity may be caused by organic or inorganic constituents, but the organic particulates may harbor microorganisms; thus, turbid conditions may represent a threat of waterborne disease (see Chapter 6). Turbidity may be classified as both a physical parameter, because it can raise aesthetic and psychological objections by the consumer, and a microbiological parameter, because it may harbor pathogens and impede the effectiveness of disinfection. Note: Inorganic constituents

have no notable health effects. In surface water supplies, most turbidity results from the erosion of very small colloidal material, including rock fragments, silt, clay, and metal oxides from the soil. Microorganisms and vegetable material may also contribute to turbidity. Wastewaters from industry and households usually contain a wide variety of turbidity-producing material. Detergents, soaps, and various emulsifying agents contribute to turbidity. Turbidity measurements are normally made on “clean” waters as opposed to wastewaters. In water treatment, turbidity is useful in defining drinking water quality and is relatively easy to measure. Given that the total coliform test is a very reliable routine test of drinking water quality but not an actual determination of pathogens in water, its use in combination with a turbidity reading and their joint evaluation can provide an extra safety factor for judging water quality changes either at the source or during distribution system sampling (DeZuane, 1997). Note: In the preliminary evaluation of raw water, when turbidity at the source of supply is under 10 units, generally only disinfection is required—with biochemical oxygen demand (BOD) at less than 1.0, coliform under 50 MPN/100 mL monthly average, and acceptable chemical parameters. When turbidity at the source exceeds 40 units, conventional treatment is considered necessary.

Turbidity is regulated by the 1996 Safe Drinking Water Act amendments and by Interim Enhanced Surface Water Treatment Rule (IESWTR) treatment optimization rules, which apply to large public water systems (those serving more than 10,000 people) that use surface water or groundwater directly influenced by surface water. The rules require continuous turbidity monitoring of individual filters and tighten allowable turbidity limits for combined filter effluent, cutting the maximum from 5 NTU to 1 NTU and the average monthly limit from 0.5 NTU (for conventional or direct filtration) to 0.3 NTU in at least 95% of the daily samples for any two consecutive months.

SOLIDS Water always contains a certain amount of particulate matter ranging from colloidal organic or inorganic matter to silts, algae, plankton or debris of all kinds. All water contaminants other than gases contribute to the solids content. Solids can be dispersed in water in both suspended and dissolved forms. Some dissolved solids may be perceived by the physical senses but fall more appropriately under the category of chemical parameters (see Chapter 8). Classified by size and state, by chemical characteristics, and by size distribution, solids in drinking water may consist of inorganic particles (salts) with small concentrations of inorganic matter or of immiscible liquids. Contributory ions are mainly carbonate, bicarbonate, chloride, sulfate, nitrate, potassium, sodium, magnesium, and calcium. Organic material such as plant fibers and biological solids (e.g., bacteria) are also common constituents of surface waters. Inorganics include clay, silt, and other soil constituents common in surface waters. These materials are often natural contaminants resulting from the erosive action of water flowing over surfaces. The filtering properties of soil generally mean that suspended solids are seldom a constituent of groundwater. Other suspended material may result from human use of the water; for example, domestic wastewater usually contains large quantities of suspended solids that are mostly organic in nature. Industrial use of water may result in a wide variety of organic or inorganic suspended impurities. Immiscible liquids such as oils and greases are often constituents of wastewater. The solids parameter is used to evaluate and measure all suspended and dissolved matters in water. Solids are classified (in spite of their chemical composition) among the physical parameters of water quality. In water, suspended material is objectionable because it provides adsorption sites for biological and chemical agents. These adsorption sites provide a protective barrier for attached microorganisms against the chemical action of chlorine disinfectants. Suspended solids in water may be de-

graded biologically, resulting in objectionable byproducts. These factors make the removal of these solids of great concern in the production of clean, safe drinking water and wastewater effluent. In water treatment, the most effective means of removing solids from water is by filtration; however, some solids (including colloids and other dissolved solids) cannot be removed by filtration. Several different tests may be performed on raw and treated waters with regard to solids:

- Total dissolved solids (TDS) in water samples are limited to the solids in solution. The recommended TDS upper limit is 500 mg/L.
- Settleable solids are solids in suspension that can be expected to settle by gravity only in a quiescent state, such as is found in an oversized settling tank. The period of time must be defined. Commonly used in the analysis of sewage, this test may provide data useful to evaluate the sedimentation process, but only when dealing with very high turbidity.
- Suspended solids (SS or TSS), also called suspended matter, are solids that are not dissolved. They have little or no significance for domestic water consumption where turbidity provides a proportional if not equivalent value but with easier determination.
- Total solids are all of the solids contained in the water sampled, as determined by evaporation and drying.
- Volatile solids are made up of organic chemicals.
- Conductance (specific conductance) is a measure of the electric current in the water sample carried by the ionized substances; therefore, dissolved solids are basically related to this measure, which is also influenced by the good conductivity of inorganic acids, bases, and salts, as well as the poor conductivity of organic compounds. The methods prescribed by Standard Methods (APHA-AWWA-WEF, 2017) for the determination of solids include the following:
- Total solids dried at 103°C to 105°C
- Total dissolved solids dried at 180°C
- Total suspended solids dried at 103°C to 105°C
- Fixed and volatile solids ignited at 550°C
- Settleable solids (Imhoff cone, volumetric, gravimetric)
- Total, fixed, and volatile solids in solid or semisolid samples

pH Raw water examined for potential use as drinking water has an expected pH value between 4 and 9, but it is more than likely that encountered values will be between 5.5 and 8.6. What does this mean? pH is defined as the negative log base 10 of the hydrogen ion concentration: $\text{pH} = -\log_{10}[\text{H}^+]$ (7.2)

The pH changes one unit for every power of ten change in $[\text{H}^+]$; for example, water with a pH of 3 has 100 times the amount of $[\text{H}^+]$ as that found in water with a pH of 5. Remember that, because $\text{pH} = -\log_{10}[\text{H}^+]$, the pH will decrease as $[\text{H}^+]$ increases. The pH of water is controlled by the equilibrium achieved by dissolved compounds in the system. In natural waters, the pH is primarily a function of the carbonate system, which is composed of carbon dioxide, carbonic acid, bicarbonate, and carbonate. Acid inputs to a water system may substantially alter the pH. The main sources of acid include acid mine drainage and atmospheric acid deposition.

Low-pH water may corrode distribution pipes in potable water plants. The pipes may be costly to replace, and the corrosion may release metal ions such as copper, lead, zinc, and cadmium into the treated drinking water. Ingestion of heavy metals may pose substantial health risks to humans. According to the Safe Drinking Water Act, the minimum and maximum allowable pH range for potability is 6.5 to 8.5. Note: The role of pH in water is also associated with corrosivity, hardness, acidity, chlorination, coagulation, carbon dioxide stability, and alkalinity. The pH of water affects treatment unit processes. Any change in the pH of source water should be investigated, as pH is a relatively stable parameter over the short term and any unusual change may indicate a major event.

ALKALINITY Alkalinity is a measure of the ability of water to absorb hydrogen ions without significant pH change. Simply stated, alkalinity is a measure of the buffering capacity of water and is thus a mea-

sure of the ability or capacity of water to neutralize acids. The major chemical constituents of alkalinity in natural water supplies are bicarbonate, carbonate, and hydroxyl ions. These compounds are mostly the carbonates and bicarbonates of sodium, potassium, magnesium, and calcium. These constituents originate from carbon dioxide (from the atmosphere and occurring as a byproduct of microbial decomposition of organic material) or minerals (primarily from chemical compounds dissolved from rocks and soil). Highly alkaline water is unpalatable; however, this condition has little known significance on human health. The principal problem with alkaline water is the reactions that occur between alkalinity and certain substances in the water. The resultant precipitate can foul water system equipment. Alkalinity levels also affect the efficiency of certain water treatment processes, especially the coagulation process. Note: Total alkalinity is determined by titration with sulfuric acid or other strong acids of known strength to the end point of indicators (APHA-AWWA-WEF, 2017). The result is expressed in mg/L of equivalent calcium carbonate. **HARDNESS** Water hardness is commonly defined as the sum of the polyvalent cations dissolved in the water. The most common cations are calcium and magnesium, although iron, strontium, and manganese may contribute. Hardness is usually reported as an equivalent quantity of calcium carbonate. Generally, waters are classified according to degree of hardness, as shown in Table 7.1. Hardness is primarily a function of the geology of the area with which the surface water is associated. Waters underlain by limestone are prone to hard water because rainfall, which is naturally acidic because it contains carbon dioxide gas, continually dissolves the rock and carries the dissolved cations into the water system. Standard Methods (APHA-AWWA-WEF, 2017) recommends measuring hardness as follows:

$$\text{Hardness} = 2497(\text{Ca}) + 4.118(\text{Mg}) \quad (7.3)$$

where total calcium (Ca) and total magnesium (Mg) are expressed in mg/L. Hardness can also be measured using the EDTA titration method (APHA-AWWA-WEF, 2017).

SOLUBILITY Solubility is a term often used in connection with water treatment, laboratory analyses, and chemical and physical studies of water, even though solubility is not a general, physical, or chemical parameter. To understand solubility, you must also understand the concept of a water solution, which is a homogeneous liquid comprised of a solvent (the substance that dissolves another substance) and a solute (the substance that dissolves in the solvent). Simply stated, solubility is defined as the mass of substance contained in a solution that is in equilibrium with an excess of the substance.

Chemical Drinking Water Parameters INTRODUCTION When one considers all of the chemicals that can be in water, it is almost overwhelming to try to comprehend the possible number of them—acrylamide, antimony, arsenic benzene, boron bromate, lead, mercury, nickel nitrate, nitrite, selenium, vinyl chloride. The list it is long and mind-boggling. This chapter does not look at each organic or inorganic chemical individually; instead, we look at general chemical parameter categories such as dissolved oxygen (DO) organics (i.e., biochemical oxygen demand and chemical oxygen demand), synthetic organic chemicals (SOCs), volatile organic chemicals (VOCs), total dissolved solids (TDS), fluoride, metals, and nutrients—the major chemical parameters of concern.

ORGANIC CHEMICALS Natural organics contain carbon and consist of biodegradable organic matter such as wastes from biological material processing, human sewage, and animal feces. Microbes aerobically break down the complex organic molecules into simpler, more stable end products. Microbial degradation yields end products such as carbon dioxide, water, phosphate, and nitrate. Organic particles in water may harbor harmful bacteria and pathogens. Infection by microorganisms may occur if the water is used

for primary contact or as a raw drinking water source. Treated drinking water will not present the same health risks. In a potable drinking water plant, all organics should be removed from the water before disinfection (see Chapter 11). Organic chemicals also contain carbon; they are substances that come directly from, or are manufactured from, plant or animal matter. Plastics provide a good example of organic chemicals obtained from petroleum, which is derived from plant and animal matter. Some organic chemicals released by decaying vegetation occur naturally and by themselves tend not to pose health problems when they get into our drinking water; however, more serious problems are caused by the more than 100,000 different manufactured or synthetic organic chemicals in commercial use today. These include paints, herbicides, synthetic fertilizers, pesticides, fuels, plastics, dyes, preservatives, flavorings, and pharmaceuticals, to name a few. Many organic materials are soluble in water and are toxic, and many can be found in public water supplies. The presence of organic matter in water is troublesome. Organic matter causes: “(1) color formation, (2) taste and odor problems, (3) oxygen depletion in streams, (4) interference with water treatment process, and (5) the formation of halogenated compounds when chlorine is added to disinfect water” (Tchobanoglous and Schroeder, 1987). Remember that organics in natural water systems may come from natural sources or may result from human activities. Generally, organic matter in water comes primarily from natural sources, including decaying leaves, weeds, and trees; the amount of these materials present in natural waters is usually low. Anthropogenic (manmade) sources of organic substances include pesticides and other synthetic organic compounds. Again, many organic compounds are soluble in water, and surface waters are more prone to contamination by natural organic compounds than are groundwaters. In water, dissolved organics are usually divided into two categories: biodegradable and nonbiodegradable. Biodegradable (able to break down) material consists of organics that can be used for food by naturally occurring microorganisms within a reasonable length of time. Alcohols, acids, starches, fats, proteins, esters, and aldehydes are the main constituents of biodegradable materials. They may result from domestic or industrial wastewater discharges, or they may be end products of the initial microbial decomposition of plant or animal tissue. Biodegradable organics in surface waters cause problems mainly associated with the effects that result from the action of microorganisms. As the microbes metabolize organic material, they consume oxygen. When this process occurs in water, the oxygen consumed is dissolved oxygen (DO). If the oxygen is not continually replaced in the water by artificial means, the DO level will decrease as the organics are decomposed by the microbes. This need for oxygen is known as the biochemical oxygen demand (BOD), which is the amount of dissolved oxygen demanded by bacteria to break down the organic materials during the stabilization action of the decomposable organic matter under aerobic conditions over a 5-day incubation period at 20°C (68°F). This bioassay test measures the oxygen consumed by living organisms using the organic matter contained in the sample and dissolved oxygen in the liquid. The organics are broken down into simpler compounds, and the microbes use the energy released for growth and reproduction. A BOD test is not required for monitoring drinking water. Note: The more organic material in the water, the higher the BOD exerted by the microbes will be. Note also that some biodegradable organics can cause color, taste, and odor problems. Nonbiodegradable organics are resistant to biological degradation. Good examples are the constituents of woody plants, including tannic and lignic acids, phenols, and cellulose, which are found in natural water systems and are considered refractory (resistant to biodegradation). Some polysaccharides with exceptionally strong bonds and benzene (for example, associated with the refining of petroleum) with its ringed structure are essentially nonbiodegradable. Cer-

tain nonbiodegradable chemicals can react with oxygen dissolved in water. The chemical oxygen demand (COD) is a more complete and accurate measurement of the total depletion of dissolved oxygen in water. Standard Methods for the Examination of Water and Wastewater (APHA-AWWA-WEF, 2017) defines COD as a test that provides a measure of the oxygen equivalent of that portion of the organic matter in a sample that is susceptible to oxidation by a strong chemical oxidant. Note: Chemical oxygen demand (COD) is not normally used to monitor water supplies but is often used to evaluate contaminated raw water.

synthetic organic chemicals Synthetic organic chemicals (SOCs) are manmade and are often toxic to humans. More than 50,000 SOCs are in commercial production today, including common pesticides, carbon tetrachloride, chloride, dioxin, xylene, phenols, and aldicarb. Unfortunately, even though they are so prevalent, little information has been collected on these toxic substances. Determining definitively just how dangerous many of these SOCs are is rather difficult. **Volatile organic chemicals** Volatile organic chemicals (VOCs) are a particularly dangerous type of organic chemical. VOCs are absorbed through the skin during contact with water—as in the shower or bath. Hot water exposure allows these chemicals to evaporate rapidly, and they are harmful if inhaled. VOCs can be found in any tap water, regardless of where one lives and the water supply source.

TOTAL DISSOLVED SOLIDS Solids in water occur either in solution or in suspension, and they are distinguished by passing the water sample through a glass-fiber filter. By definition, suspended solids are retained on top of the filter, and dissolved solids pass through the filter with the water. When the filtered portion of the water sample is placed in a small dish and then evaporated, the solids in the water remain as residue in the evaporating dish. This material is referred to as total dissolved solids (TDS). Dissolved solids may be organic or inorganic. Water may come into contact with these substances within the soil, on surfaces, and in the atmosphere. The organic dissolved constituents of water come from the decay products of vegetation, from organic chemicals, and from organic gases. Removing these dissolved minerals, gases, and organic constituents is desirable, because they may cause physiological effects and produce an aesthetically displeasing color, taste, or odor. Note: In water distribution systems, high levels of TDS indicate high conductivity with consequently higher ionization in corrosion control; however, high TDS levels also indicate the greater likelihood of a protective coating, a positive factor in corrosion control.

FLUORIDE Water fluoridation prevents tooth decay primarily through frequent, daily contact with low levels of fluoride (CDC, 2011). Even today, with other available sources of fluoride, studies show that water fluoridation reduces tooth decay by about 25% over a person's lifetime; in fact, drinking water containing a proper amount of fluoride can reduce tooth decay as much as 65% in children between the ages 12 and 15. It should be pointed out, however, that water fluoridation is not necessarily the safe public health measure we have been led to believe it is (Mullenix, 1997). Concerns about uncontrolled dosage, accumulation in the body over time, and effects beyond the teeth (brain as well as bones) have not been resolved, although most authorities believe that a moderate amount of fluoride ions (F^-) in drinking water contributes to good dental health. Fluoride is seldom found in appreciable quantities of surface waters and appears in groundwater in only a few geographical regions, although it is sometimes found in a few types of igneous or sedimentary rocks. Fluoride is toxic to humans in large quantities (the key words here being “large quantities”) and is also toxic to some animals. Few would argue that small concentrations of fluoride (about 1.0 mg/L in drinking water) can be beneficial; however, when the concentration of fluoride in

untreated natural water supplies is excessive, either alternative water supplies must be used or treatment must be applied to reduce the fluoride concentration, because excessive amounts of fluoride cause mottled or discolored teeth, a condition called dental fluorosis. The bottom line on fluoridation is that the widespread availability of fluoride through water fluoridation, toothpaste, and other sources has resulted in the steady decline of dental caries throughout the United States.

HEAVY METALS Heavy metals are elements with atomic weights between 63.5 and 200.5 and specific gravity greater than 4.0. Living organisms require trace amounts of some heavy metals, including cobalt, copper, iron, manganese, molybdenum, vanadium, strontium, and zinc. Excessive levels of essential metals, however, can be detrimental to the organism. Non-essential heavy metals of particular concern to surface water systems are cadmium, chromium, mercury, lead, arsenic, and antimony. Heavy metals in water are classified as either nontoxic or toxic. Only those metals that are harmful in relatively small amounts are labeled toxic; other metals fall into the nontoxic group. In natural waters (other than in groundwaters), sources of metals include dissolution from natural deposits and discharges of domestic, agricultural, or industrial wastes. All heavy metals exist in surface waters in colloidal, particulate, and dissolved phases, although dissolved concentrations are generally low. Colloidal and particulate metals may be found in hydroxides, oxides, silicates, or sulfides or they may be adsorbed to clay, silica, or organic matter. The soluble forms are generally ions or unionized organometallic chelates or complexes. The solubility of trace metals in surface waters is predominately controlled by water pH, the type and concentration of ligands on which the metal could adsorb, and the oxidation state of the mineral components and the redox environment of the system. The behavior of metals in natural waters is a function of the substrate sediment composition, the suspended sediment composition, and the water chemistry. Sediment composed of fine sand and silt will generally have higher levels of adsorbed metal than will quartz, feldspar, and detrital carbonate-rich sediment. The water chemistry of the system controls the rate of adsorption and desorption of metals to and from sediment. Adsorption removes the metal from the water column and stores the metal in the substrate. Desorption returns the metal to the water column, where recirculation and bioassimilation may take place. Metals may be desorbed from the sediment if the water experiences increases in salinity, decreases in redox potential, or decreases in pH. Although heavy metals such as iron and manganese do not cause health problems, they do impart a noticeable bitter taste to drinking water, even at very low concentrations. These metals usually occur in groundwater in solution, and these and others may cause brown or black stains on laundry and on plumbing fixtures.

NUTRIENTS Nitrogen, an extremely stable gas, is the primary component (78%) of the Earth's atmosphere. The nitrogen cycle is composed of four processes. Three of the processes—fixation, ammonification, and nitrification—convert gaseous nitrogen into usable chemical forms. The fourth process, denitrification, converts fixed nitrogen back to the unusable gaseous nitrogen state. Nitrogen occurs in many forms in the environment and takes part in many biochemical reactions. Major sources of nitrogen include runoff from animal feedlots, fertilizer runoff from agricultural fields, municipal wastewater discharges, and certain bacteria and blue-green algae that obtain nitrogen directly from the atmosphere. Certain forms of acid rain can also contribute nitrogen to surface waters. Nitrogen in water in the form of nitrate (NO_3) indicates that the water may be contaminated with sewage. Nitrates can also enter the groundwater from chemical fertilizers used in agricultural areas. Excessive nitrate concentrations in drinking water pose an immediate health threat to infants, both human and animal, and can cause death. The bacteria com-

monly found in the intestinal tract of infants can convert nitrate to highly toxic nitrites (NO_2), which can replace oxygen in the bloodstream and result in oxygen starvation, causing a bluish discoloration of the infant (“blue baby” syndrome). Note: Lakes and reservoirs usually have less than 2 mg/L of nitrate measured as nitrogen. Higher nitrate levels are found in groundwater ranging up to 20 mg/L, but much higher values are detected in shallow aquifers polluted by sewage or excessive use of fertilizers. Phosphorus is an essential nutrient that contributes to the growth of algae and eutrophication of lakes, although its presence in drinking water has little effect on health. In aquatic environments, phosphorus is found in the form of phosphate and is a limiting nutrient. If all phosphorus is used up, plant growth ceases, no matter the amount of nitrogen available. Many bodies of freshwater currently experience influxes of nitrogen and phosphorus from outside sources. The increasing concentration of available phosphorus allows plants to assimilate more nitrogen before the phosphorus is depleted. If sufficient phosphorus is available, high concentrations of nitrates will lead to phytoplankton (algae) and macrophyte (aquatic plant) production. Major sources of phosphorus include phosphates in detergents, fertilizer and feedlot runoff, and municipal wastewater discharges. The USEPA’s 1976 publication *Quality Criteria for Water* recommended a phosphorus criterion of 0.10 $\mu\text{g/L}$ (elemental) phosphorus for marine and estuarine waters but established no freshwater criterion.

SUMMARY The biological, physical, and chemical condition of our water is of enormous concern to us all, because we must live in such intimate contact with water. When these parameters shift and change, these changes affect us, often in ways science cannot yet define for us. Water pollution is an external element that can and does significantly affect our water, but what exactly is water pollution? We quickly learn that the sources of water pollution do not always travel a direct path to water. Controlling what enters our water is difficult, because the hydrologic cycle carries water (and whatever it picks up along the way) through all of our environment’s media, thus affecting the biological, physical, and chemical condition of the water we must drink to live. Water pollution is discussed further in Chapter 9.

INTRODUCTION Is drinking water contamination really a problem—a serious problem? The answer to the first part of the question depends on where your water comes from. As to the second part of the question, the reader is referred to a book (or the film based on the book) that concerns a case of toxic contamination that might be familiar—*A Civil Action*, by Jonathan Harr. The book and film portray the legal repercussions connected with polluted water supplies in Woburn, Massachusetts. Two wells became polluted with industrial solvents, apparently causing 24 of the town’s children who lived in neighborhoods supplied by those wells to contract leukemia and die over a span of 12 years—a rate several times the national average for a community of its size. The families involved sued two companies for dumping toxic waste. Their attorney, Jan Schlichtmann, emphasized that Woburn was only one example of an underlying pathology that threatens many other communities. Many who have read the book or have seen the movie may mistakenly get the notion that Woburn, a toxic “hot spot,” is a rare occurrence. Nothing could be further from the truth. Toxic “hot spots” abound. Most striking are areas of cancer clusters, a short list of which includes not only Woburn but also Storrs, Connecticut, where wells polluted by a landfill are suspected of sickening and killing residents in nearby homes. In Bellingham, Washington, pesticide-contaminated drinking water is thought to be linked to a sixfold increase in childhood cancers. Cancer is now the primary cause of childhood death from disease. Drinking water contamination is a problem—a very serious problem. In this chapter, we discuss a wide range of water contaminants, the sources of

these contaminants, and their impact on drinking water supplies from both surface water and groundwater sources. Moreover, before moving on to an in-depth discussion of drinking water pollution and many of the contaminants involved, it is appropriate to highlight two drinking water crises that have occurred in the United States: the Gold King Mine spill (USEPA, 2015a,b) and the lead-contaminated drinking water in Flint, Michigan (Hanna-Attisha et al., 2015; United Way, 2016). GOLD KING MINE SPILL On August 5, 2014, the U.S. Environmental Protection Agency (USEPA) conducted a mine site investigation of the abandoned Gold King Mine above the old adit (a mine tunnel) to

- Assess the ongoing water releases from the mine.
- Treat mine water.
- Assess the feasibility of further mine remediation.

During the excavation required for the investigation the heavy equipment disturbed loose material around a soil “plug” at the mine entrance, spilling about 3 million gallons of pressurized water stored behind the collapsed material into Cement Creek, a tributary of the Animas River. The spill volume associated with the release on August 5 was calculated to be approximately 3 million gallons based on flow rates. Discharge rates from the mine as of November 5, 2015, averaged around 600 gallons per minute. It is important to point out, for context, that multiple mines are located along the upper Animas, and historically there have been considerable discharges at each mine site. The Red and Bonita mines, just below the Gold King Mine, currently discharge about 300 gallons per minute. One of the most striking effects of the Gold King Mine spill was the color change clearly visible in Cement Creek and Animas River and to a lesser degree downstream almost to the San Juan River. The iron from the acid mine drainage precipitated out into the water as a result of the rise in pH, turning it yellow. Old-time goldpanners and other sluice miners refer to the resulting red, orange, and yellow solids as “yellow boy.” Typically, as more water is mixed in (dilution is the solution to pollution, according that mythical hero Hercules, who arguably might have been the world’s first environmental engineer), the iron and other metals become even more dilute or get attached to sediments, causing them to drop out of the water, sink, and settle into river bottom sediments. The water color then returns to normal. But, and this is the gist of this text, what appears normal in surface water bodies may not actually be normal because, as in the case of the Animas River and thousands of other polluted streams, what we are able to see at the surface does not in any way certify the quality of the water that is contained within the water body. “Momma, this water is dirty!” “Momma, this water is smelly!” “Momma, this water tastes yucky!” “Momma, I drank the water and now I feel icky!” Does this refrain sound at all familiar to you? Is it something you’ve ever heard a child utter? In modern countries, such as the United States, has this refrain ever even been spoken? Well, let’s have a conversation about this issue. Most likely, this refrain does not sound familiar to you. It’s possible that you’ve heard it, but you may not have heard it spoken in English. Such complaints may be spoken in any of many different languages and too often are heard in underdeveloped nations. Underdeveloped nation? What exactly is an underdeveloped nation? In keeping with Voltaire and his famous saying, “If you wish to converse with me, please define your terms,” so, for our purposes here, let’s define the term as a nation that, because of several possible conditions, is lacking access to job opportunities, food, healthcare, education, housing, and—most importantly in the real world and in this book—safe drinking water (the key word being safe). It has been estimated that 780 million people do not have access to an improved drinking water source and that over 800,000 children younger than 5 years of age perish each year from diarrhea, mostly in underdeveloped countries. But, what is an improved drinking water source? The

FIGURE 9.1 Rainwater collection. (Illustration by F.R. Spellman and K. Welsh.)

World Health Organization/UNICEF Joint Monitoring Programme for Water Supply and Sanitation has defined “improved” water sources as follows (WHO/ UNICEF, 2017):

- Piped water into a dwelling; water can be drawn from a common household tap
- Piped water into a yard/plot
- Public taps/standpipes
- Tubewells/boreholes
- Protected dug wells
- Protected springs
- Rainwater collection (see Figure 9.1)
- Bottled water, if the secondary source used by the household for cooking and personal hygiene is improved

Water sources that are not considered “improved” include the following:

- Unprotected dug wells
- Unprotected springs
- Vendor-provided water
- Cart with a small tank/drum
- Bottled water, if the secondary source used by the household for cooking and personal hygiene is unimproved
- Tanker-truck
- Surface water

It should be clear now as to what an improved drinking water source is and what an unimproved source is. So, getting back to our earlier question, are complaints about drinking water heard only in underdeveloped countries? Unfortunately, no. They can be heard even in this country, depending on geographical location and personal circumstance. Your experience with the tap water from your own kitchen sink is probably okay, but consider the residents of Flint, Michigan, for example. Many readers are no doubt familiar with the Flint, Michigan, fiasco, but for those of you who are not, let’s summarize. In April 2014, Flint changed its water source from treated Detroit Water and Sewerage Department water, which was sourced from the Detroit River and Lake Huron, to water from the Flint River, a very corrosive water source. The city experienced a series of problems with the new drinking water source that culminated in the discovery of lead contamination, a grave public health hazard. Flint River water that was treated improperly (or not treated at all) caused lead, scale, and who knows what else that had built up in the aging pipes (see Figure 9.2) to leach into the water supply, resulting in extremely elevated levels of lead, a heavy metal neurotoxin. It is estimated that, in Flint, somewhere between 6000 and 12,000 children have been exposed to tap water, a supposedly improved water source, with high levels of lead. These lead levels were high enough to cause a range of serious health issues (United Way, 2016). Due to the change in water source, the percentage of Flint children with elevated blood lead levels may have raised from about 2.5% in 2013 to as much as 5% in 2015 (Hanna-Attisha et al., 2015). Some speculate that the water change may have caused an outbreak of Legionnaires’ disease in the county that killed 10 people and made more than 70 people ill. The experience of Flint’s lead-contaminated water supply suggests that children’s complaints about the water they are drinking could actually be heard here in the United States. This, of course, raises other questions. Are there other, as yet undiscovered cities in the United States distributing contaminated water? Without a doubt, due to this country’s aging infrastructure. Many water distribution systems are more than 100 years old and in dire need of upgrading. The main problem is money. Replacing old and deteriorating distribution systems is not cheap. When city managers, city councils, and utility directors are advised that they need to upgrade their water system to the tune of millions of dollars, they immediately ask, “Where would we get the money to do that?” If they contemplate raising funds by making rate payers pay the bill, their political careers or appointed positions will quickly be over. Well, how about the states and federal government? Can’t they come up with the funds needed to upgrade such critical infrastructure? Again, though, their answer is, “Where would we get the money to do that?” Unfortunately, no action can be expected until a Flint-type event occurs, one that has a highly

emotional impact because of potential damage to children and others. The press would have to be all over the situation, and the politicians would have to point fingers here, there, and everywhere (except toward themselves). Funding that is difficult or impossible to find to retrofit aging municipal water distribution systems is one thing, but allowing what occurred in Flint is an entirely different matter. After my years of teaching undergraduate and graduate-level environmental health courses, including waterworks operation, as well as short courses in water and wastewater treatment at Virginia Tech for operators and for those seeking licensure as operators, I was totally surprised by what happened in Flint, Michigan. Water operators, water administrators, waterworks managers, waterworks environmental engineers, and other waterworks personnel know that incoming water must be sampled and tested for quality. Moreover, during the treatment of water as it flows from unit process to unit process, it must be sampled and tested. At the completion of treatment and prior to discharge to the distribution system the treated water must be sampled and treated again. This sequence of sampling and treating is not just nice to do; it is not just best practices—it is the absolute law of the land, and there is a distinct moral obligation to provide the best and safest drinking water possible. What exactly occurred at Flint may never be fully revealed; however, one thing is absolutely certain—people did not do what they were trained and obligated to do. They did not deliver safe drinking water to the consumer. And, because of their incompetence, violation of law, or just plain stupidity or immorality, we are now likely to hear, “Get the lead out of the water, please!”

SOURCES OF CONTAMINANTS If one were to list all of the sources of contaminants and the contaminants themselves (the ones that can and do foul our water supply systems), along with a brief description of each contaminant, that list would be long enough to fill a book. To give the reader some idea of the magnitude of the problem, following is a very condensed list of selected sources and contaminants (the “short list”). Note: Keep in mind that when we specify “water pollutants” we are in most cases speaking about pollutants that somehow get into the water (by whatever means) due to the interactions of the other two environmental mediums: air and soil. Probably the best example of this is the acid rain phenomenon. Pollutants originally emitted only into the atmosphere land on Earth and affect both soil and water. Consider that 69% of the anthropogenic lead and 73% of the mercury in Lake Superior have reached it by atmospheric deposition (Hill, 1997).

- Subsurface percolation—Hydrocarbons, metals, nitrates, phosphates, microorganisms, cleaning agents (e.g., trichloroethylene, or TCE)
- Injection wells—Hydrocarbons, metals, non-metal inorganics, organic and inorganic acids, organics, microorganisms, radionuclides
- Land application—Nitrogen, phosphorus, heavy metals, hydrocarbons, microorganisms, radionuclides
- Landfills—Organics, inorganics, microorganisms, radionuclides
- Open dumps—Organics, inorganics, microorganisms
- Residential (local) disposal—Organic chemicals, metals, non-metal inorganics, inorganic acids, microorganisms
- Surface impoundments—Organic chemicals, metals, non-metal inorganics, inorganic acids, microorganisms, radionuclides
- Waste mine tailings—Arsenic, sulfuric acid, copper, selenium, molybdenum, uranium, thorium, radium, lead, manganese, vanadium
- Waste piles—Arsenic, sulfuric acid, copper, selenium, molybdenum, uranium, thorium, radium, lead, manganese, vanadium
- Materials stockpiles—Aluminum, iron, calcium, manganese, sulfur, and traces of arsenic, cadmium, mercury, lead, zinc, uranium, and copper (coal piles); metals and non-metals; microorganisms (other materials piles)
- Graveyards—Metals, non-metals, microorganisms
- Animal burial—Site-specific contamination, depending on disposal practices (e.g., surface or subsurface), hydrology, proximity of the site to water sources, type and amount of disposed material, cause of

death • Aboveground storage tanks—Organics, metal and non-metal inorganics, inorganic acids, microorganisms, radionuclides • Underground storage tanks—Organics, metal, inorganic acids, microorganisms, radionuclides • Containers—Organics, metal and non-metal inorganics, inorganic acids, microorganisms, radionuclides • Open burning and detonating sites—Inorganics (including heavy metals), organics (including TNT) • Radioactive waste disposal sites—Radioactive cesium, plutonium, strontium, cobalt, radium, thorium, uranium • Pipelines—Organics, metals, inorganic acids, microorganisms • Material transport and transfer operations—Organics, metals, inorganic acids, microorganisms, radionuclides • Irrigation practices—Fertilizers, pesticides, naturally occurring contamination, sediments • Pesticide applications—Estimated at 1200 to 1400 active ingredients, including alachlor, aldicarb, atrazine, bromacil, carbofuran, cyanazine, dibromochloropropane (DBCP), dimethyl tetrachloroterephthalate (DCPA), 1,2-dichloropropane, dyfonate, ethylene dibromide (EDB), metolachlor, metribyzen, oxalyl, siazine, 1,2,3-trichloropropane (the extent of groundwater contamination cannot be determined with current data) • Animal feeding operations—Nitrogen, bacteria, viruses, phosphates • Deicing salts applications—Chromate, phosphate, ferric ferrocyanide, Na-ferrocyan, chlorine • Urban runoff—Suspended solids and toxic substances, especially heavy metals and hydrocarbons, bacteria, nutrients, petroleum residues • Percolation of atmospheric pollutants—Sulfur and nitrogen compounds, asbestos, heavy metals • Mining and mine drainage—Acids, toxic inorganics (heavy metals), nutrients (coal); radium, uranium, fluorides (phosphate); sulfuric acid, lead, cadmium, arsenic, sulfur, cyan (metallic ores) • Production wells—Oil wells (1.2 million abandoned production wells); farm irrigation wells; installation, operation, and plugging of all wells • Construction excavation—Pesticides, diesel fuel, oil, salt, various others • Pharmaceuticals and personal care products (PPCPs)—Any product used by individual for personal health or cosmetic reason or used by agribusiness to enhance growth or health of livestock

Note: Before we discuss specific water pollutants, we must examine several terms important to the understanding of water pollution. One of these is point source. The USEPA defines a point source as “any single identifiable source of pollution from which pollutants are discharged, e.g., a pipe, ditch, ship, or factory smokestack.” For example, the outlet pipes of an industrial facility or a municipal wastewater treatment plant are point sources. In contrast, non-point sources are widely dispersed sources and are a major cause of stream pollution. An example of a

non-point source of pollution is rainwater carrying topsoil and chemical contaminants into a river or stream. Some of the major sources of non-point source pollution include water runoff from farming, urban areas, forestry, and construction activities. The word runoff signals a non-point source that originated on land. Runoff may carry a variety of toxic substances and nutrients, as well as bacteria and viruses with it. Non-point sources now comprise the largest source of water pollution, contributing approximately 65% of the contamination in qualityimpaired streams and lakes.

RADIONUCLIDES When radioactive elements decay, they emit alpha, beta, or gamma radiations caused by transformation of the nuclei to lower energy states. In drinking water, radioactivity can be from natural or artificial radionuclides (the radioactive metals and minerals that cause contamination). These radioactive substances in water are of two types: radioactive minerals and radioactive gas. The U.S. Environmental Protection Agency (USEPA) reports that some 50 million Americans face increased cancer risk because of radioactive contamination of their drinking water. Because of their occurrence in drinking water and their effects on human health, the natural radionuclides of chief concern are radium-226,

radium-228, radon-222, and uranium. The source of some of these naturally occurring radioactive minerals is typically associated with certain regions of the country where mining is active or was active in the past. Mining activities expose rock strata, most of which contain some amount of radioactive ore. Uranium mining, for example, produces runoff. Radioactive contamination also occurs when underground streams flow through various rockbed and geologic formations containing radioactive materials. Other sources of radioactive minerals that may enter water supplies are smelters and coal-fired electrical generating plants. Also contributing to radioactive contamination of water are nuclear power plants, nuclear weapons facilities, radioactive materials disposal sites, and mooring sites for nuclear-powered ships. Hospitals contribute radioactive pollution when they dump low-level radioactive wastes into sewers; some of these radioactive wastes eventually find their way into water supply systems. Although radioactive minerals such as uranium and radium in water may present a health hazard in particular areas, a far more dangerous threat exists in the form of radon. Radon is a colorless, odorless gas created by the natural decay of minerals in the soil. Normally present in all water in minute amounts, radon is especially concentrated in water that has passed through rock strata of granite, uranium, or shale. Radon enters homes from the soil beneath through cracks in the foundation or through crawl spaces and unfinished basements, as well as in tainted water. Radon is considered to be the second leading cause of lung cancer in the United States (about 20,000 cases each year), second only to cigarette smoking. Contrary to popular belief, radon is not a threat from surface water (lakes, rivers, or above-ground reservoirs), because radon dissipates rapidly when water is exposed to air. Even if the water source is groundwater, radon is still not a threat if the water is exposed to air (aerated) or if it is processed through an open tank during treatment. Studies have shown that where high concentrations of radon are detected within the air in a house most of that radon has come through the foundation and from the water; however, hot water used for showers, baths, or cooking (hot water) can release high concentrations of radon into the air. Still, radon is primarily a threat from groundwater taken directly from an underground source—either a private well or from a public water supply whose treatment of the water does not include exposure to air. Because radon in water evaporates quickly into the air, the primary danger is from inhaling it, not from drinking it.

THE CHEMICAL COCKTAIL If we were to take the time to hold a full glass of water and inspect the contents, we might find that the contents appear cloudy or colored, making us think that the water is not fit to drink. Or, the contents might look fine but an odor of chlorine is prevalent. Most often, though, we simply draw water from the tap and either drink it or use it to cook dinner. The fact is that typically a glass of treated water is a chemical cocktail (Kay, 1996). Water utilities in communities seek to protect the public health by treating raw water with certain chemicals; what they are in essence doing is providing a drinking water product that is a mixture of various treatment chemicals and their byproducts. Water treatment facilities typically add chlorine to disinfect, but chlorine can produce contaminants. Another concoction is formed when ammonia is added for disinfection. Alum and polymers are added to the water to settle out various contaminants. The water distribution system and appurtenances must be protected from pipe corrosion, so the water treatment facility adds caustic soda, ferric chloride, and lime, which in turn increase the aluminum, sulfates, and salts in the water. Thus, when we hold that glass of water before us and we perceive a full glass of crystal clear, refreshing water, what we are really seeing is a concoction of many chemicals mixed with water, forming the chemical cocktail. The most common chemical additives used in water treatment are fluorides, chlorine, and flocculants. Because fluorides have already

been discussed, the discussion in the following sections focuses on the byproducts of chlorine and flocculant additives.

byproducts of chlorine To lessen the potential impact of that water cocktail, the biggest challenge today is to make sure that the old standby, chlorine, will not produce as many new contaminants as it destroys. At the present time, arguing against the use of chlorine is difficult. Since 1908, chlorine has been used in the United States to kill off microorganisms that spread cholera, typhoid fever, and other waterborne diseases. In the 1970s, however, scientists discovered that, although chlorine does not seem to cause cancer in lab animals, when used in the water treatment process it can create a long list of byproducts that do. The byproducts of chlorine that present the biggest health concern are organic hydrocarbons, known as trihalomethanes, which are usually discussed as total trihalomethanes (TTHMs). The USEPA classifies three of these trihalomethane byproducts—chloroform, bromoform, and bromodichloromethane—as probable human carcinogens. The fourth, dibromochloromethane, is classified as a possible human carcinogen. The USEPA set the first trihalomethane limits in 1979. Most water companies met these standards initially, but the standards were tightened after passage of the 1996 Safe

Drinking Water Act (SDWA) amendments. The USEPA is continuously studying the need to regulate other cancer-causing contaminants, including haloacetic acids (HAAs), also produced by chlorination. Most people concerned with protecting public health applaud the USEPA's efforts in regulating water additives and disinfection byproducts; however, some people involved in the water treatment and supply business have expressed concern. A common concern often heard from water utilities having a tough time balancing the use of chlorine without going over the regulated limits revolves around the necessity of meeting regulatory requirements by lowering chlorine amounts to meet byproducts standards and at the same ensuring that all the pathogenic microorganisms are killed off. Many make the strong argument that, although no proven case exists that disinfection byproducts cause cancer in humans, many cases—an extensive history of cases—show that if we do not chlorinate water, then people get sick and sometimes die from waterborne disease. Because chlorination is now prompting regulatory pressure and compliance with new, demanding regulations, many water treatment facilities are looking for other options. Choosing an alternative disinfection chemical process is feeding a growing enterprise. One alternative that is currently being given widespread consideration in the United States is ozonation, which uses ozone gas to kill microorganisms. Ozonation is Europe's preferred method, and it does not produce trihalomethanes, but the USEPA does not yet recommend a wholesale switchover to ozone to replace chlorine or chlorination systems utilizing sodium hypochlorite or calcium hypochlorite. The USEPA points out that ozone also has problems, as it does not produce a residual disinfectant in the water distribution system, it is much more expensive, and in salty water it can produce another carcinogen, bromate. We discuss disinfection alternatives in greater detail in Chapter 11. At the present, what drinking water practitioners are doing (in the real world) is attempting to fine-tune water treatment. What it all boils down to is a delicate balancing act. Drinking water professionals do not want to cut back on disinfection; if anything, they would prefer to strengthen it. So, we have to ask how we can bring into parity the microbial risks versus the chemical risks. How can both risks be reduced to an acceptable level? Unfortunately, no one is quite sure how to do this. The problem really revolves around the enigma associated with a “we don't know what we don't know” scenario. The disinfection byproducts problem stems from the fact that most U.S. water systems produce the unwanted byproducts when the chlorine reacts to decayed organics: vegeta-

tion and other carbon-containing materials in water. Communities that take drinking water from lakes and rivers have a tougher time keeping the chlorine byproducts out of the tap than those that use clean groundwater. When a lot of debris is in the reservoir, a water utility may switch to alternative sources, such as wells. In other facilities, chlorine is combined with ammonia in a disinfection method called chloramination. This method is not as potent as pure chlorination, but it does prevent the production of unwanted trihalomethanes. In communities where rains wash leaves, grasses, and trees into the local water source (such as a lake or river), hot summer days can trigger algae blooms, upping the organic matter that can produce trihalomethanes. Spring runoff in many communities

exacerbates the problem. With increased runoff comes agricultural waste, pesticides, and quantities of growth falling into the water that must be dealt with. Nature's conditions in summer diminish some precursors for trihalomethanes—the bromides in salty water. Under such conditions, usually nothing unusual is visible in the drinking water; however, water that is cloudy due to silt (dissolved organics from decayed plants) could harbor trihalomethanes. Most cities today strain out the organics from their water supplies before chlorinating to prevent the formation of trihalomethanes and haloacetic acids. In other communities, the move is on to switch from chlorine to ozone and other disinfectant methods. The National Resources Defense Council (NRDC, 2003) suggested that eventually most U.S. systems will catch up with Europe in using ozone to kill resistant microbes such as *Cryptosporidium*. When this method is employed, the finishing touch is usually accomplished by filtering the water through granular activated carbon, which increases the cost for consumers (estimated at about \$100 or more per year per hookup).

Disinfection byproduct regulations* A major challenge for drinking water practitioners is how to balance the risks from microbial pathogens and disinfection byproducts. Providing protection from these microbial pathogens while simultaneously ensuring decreasing health risks to the population from disinfection byproducts (DBPs) is important. The Safe Drinking Water Act (SDWA) amendments, signed by President Clinton in 1996, required the USEPA to develop rules to achieve these goals. The Stage 1 Disinfectants and Disinfection Byproducts Rule and the Interim Enhanced Surface Water Treatment Rule are the first of a set of rules known as the Microbial and Disinfection Byproduct (MDBP) Rules. These new rules were the product of 6 years of collaboration among the water industry, environmental and public health groups, and local, state, and federal government. The schedule for implementing the MDBP Rules was established as follows:

- 1998—Final Rule, Interim Enhanced Surface Water Treatment Rule and Stage 1 Disinfectants and Disinfection Byproducts Rule (DBPR)
- 2001—Final Rule, Filter Backwash Recycling Rule and Final Rule, Long-Term 1 Enhanced Surface Water Treatment Rule
- 2002—Final Rule, Ground Water Rule and Final Rule, Long-Term 2 Enhanced Surface Water Treatment Rule and Stage 2 Disinfectants and Disinfection Byproduct Rule (DBPR)
- 2006—Under Stage 2 DBPR, community water systems serving at least 100,000 must submit initial distribution system evaluation (IDSE) monitoring plans, system-specific study plans, or 40/30 certification
- 2009—Under Stage 2 DBPR, community water systems serving 50,000 to 99,000 must submit initial distribution system evaluation (IDSE) monitoring plans, system-specific study plans, or 40/30 certification

- Adapted from USEPA, Drinking Water Priority Rulemaking: Microbial and Disinfection Byproducts Rules, EPA 816-F-01-012, U.S. Environmental Protection Agency, Washington, DC, 2001.

Other pertinent Stage 1 and 2 DBPR rules can be found in applicable USEPA regulations; see <http://water.epa.gov/lawsregs>. Public Health Concerns Most Americans drink tap water that meets all existing health standards all the time. These rules were designed to further strengthen existing drinking water standards and thus increase protection for many water systems. The USEPA's Science Advisory Board concluded in 1990 that exposure to microbial contaminants such as bacteria, viruses, and protozoa (e.g., *Giardia lamblia*, *Cryptosporidium*) was likely the greatest remaining health risk management challenge for drinking water suppliers. Acute health effects from exposure to microbial pathogens are documented, and associated illness can range from mild, to moderate cases lasting only a few days, to more severe infections that can last several weeks and may result in death for those with weakened immune systems. Disinfectants are effective in controlling many microorganisms, but they react with natural organic and inorganic matter in source water and distribution systems to form potential DBPs, many of which have been shown to cause cancer and reproductive and developmental effects in laboratory animals. More than 200 million people consume water that has been disinfected. Because of the large population exposed, health risks associated with DBPs, even if small, need to be taken seriously.

Existing Regulations

- **Microbial contaminants**—The 1989 Surface Water Treatment Rule applies to all public water systems using surface water sources or groundwater sources under the direct influence of surface water. It establishes maximum contaminant level goals (MCLGs) for viruses, bacteria, and *Giardia lamblia*. It also addresses treatment technique requirements for filtered and unfiltered systems specifically designed to protect against the adverse health effects of exposure to these microbial pathogens. The Total Coliform Rule, revised in 1989, applies to all public water systems and establishes a maximum contaminant level (MCL) for total coliforms.
- **Disinfection byproducts**—In 1979, the USEPA set an interim MCL for total trihalomethanes of 0.10 mg/L as an annual average. This applies to any community water system serving at least 10,000 people that adds a disinfectant to the drinking water during any part of the treatment process. In 1998, the USEPA established the Stage 1 Disinfectants and Disinfection Byproducts Rule, which required public water systems to use treatment measures to reduce the formation of disinfection byproducts and to meet the following specific standards:
- **Information Collection Rule**—To support the MDBP rulemaking process, the Information Collection Rule establishes monitoring and data reporting requirements for large public water systems serving at least 100,000 people. This rule was intended to provide the USEPA with information on the occurrence in drinking water of microbial pathogens and DBPs. The USEPA has collected engineering data on how public water systems currently control such contaminants as part of the Information Collection Rule.

Interim Enhanced Surface Water Treatment Rule and Stage 1 Disinfectants and Disinfection Byproducts Rule The USEPA finalized the Interim Enhanced Surface Water Treatment Rule and Stage 1 Disinfectants and Disinfection Byproducts Rule in 1998, as required by the 1996 amendments to the Safe Drinking Water Act, Section 1412(b)(2)(C). The final rules resulted from formal regulatory negotiations with a wide range of stakeholders that took place from 1992 to 1993 and in 1997.

Interim Enhanced Surface Water Treatment Rule The Interim Enhanced Surface Water Treatment Rule applies to systems using surface water or groundwater under the direct influence of surface water that serve 10,000 or more persons. The rule also includes provisions for states to conduct sanitary surveys for surface water systems regardless of system size. The rule built upon the treatment technique requirements of the Surface Water Treatment Rule with the following key additions and modifications:

- Maximum contaminant level goal (MCLG) of zero for *Cryptosporidium*
- 2-log *Cryptosporidium* removal requirements for systems that filter
- Strengthened combined filter effluent turbidity performance standards
- Individual filter turbidity monitoring provisions
- Disinfection profiling and benchmarking provisions
- Systems using groundwater under the direct influence of surface water now subject to the new rules dealing with *Cryptosporidium*
- Inclusion of *Cryptosporidium* in the watershed control requirements for unfiltered public water systems
- Requirements for covers on new finished water reservoirs
- Sanitary surveys, conducted by states, for all surface water systems regardless of size

The Interim Enhanced Surface Water Treatment Rule, with tightened turbidity performance criteria and required individual filter monitoring, was designed to optimize treatment reliability and to enhance physical removal efficiencies to minimize the *Cryptosporidium* levels in finished water. The rule also includes disinfection benchmark provisions to ensure continued levels of microbial protection while facilities take the necessary steps to comply with DBP standards. Stage 1 Disinfectants and Disinfection Byproducts Rule The final Stage 1 Disinfectants and Disinfection Byproducts Rule applies to community water systems and nontransient, noncommunity systems (including those serving fewer than 10,000 people) that add a disinfectant to the drinking water during any part of the treatment process. The final Stage 1 Disinfectants and Disinfection Byproducts Rule includes the following key provisions:

- Maximum residual disinfectant levels (MRDLs) for chlorine (4 mg/L), chloramines (4 mg/L), and chlorine dioxide (0.8 mg/L)
- Maximum contaminant level goals (MCLGs) for four trihalomethanes (chloroform, 0; bromodichloromethane, 0; dibromochloromethane, 0.06 mg/L; bromoform, 0); two haloacetic acids (dichloroacetic acid, 0; trichloroacetic acid, 0.3 mg/L); bromate (0); and chlorite (0.8 mg/L)
- Maximum residual disinfectant levels (MRDLs) for three disinfectants (chlorine, 4.0 mg/L; chloramines, 4.0 mg/L; chlorine dioxide, 0.8 mg/L)
- Maximum contaminant levels (MCLs) for total trihalomethanes, a sum of the four listed above (0.080 mg/L); haloacetic acids (HAA5) (0.060 mg/L), a sum of the two listed above plus monochloroacetic acid and monoand dibromoacetic acids; and two inorganic disinfection byproducts (chlorite, 1.0 mg/L; bromate, 0.010 mg/L)
- A treatment technique for removal of DBP precursor material

The term maximum residual disinfectant level (MRDL) (not included in the SDWA) was created during the negotiations to distinguish disinfectants (because of their beneficial use) from contaminants. The final rule includes monitoring, reporting, and public notification requirements for these compounds. This final rule also describes the best available technology (BAT) upon which the MRDLs and MCLs are based.

Subsequent Rules Long-Term 1 Enhanced Surface Water Treatment Rule Whereas the Stage 1 Disinfectants and Disinfection Byproducts Rule applied to systems of all sizes, the Interim Enhanced Surface Water Treatment Rule applied only to systems serving 10,000 or more people. The Long-Term 1 Enhanced Surface Water Treatment Rule strengthened microbial controls for small systems (i.e., those systems serving fewer than 10,000 people). The rule also prevents significant increases in microbial risk where small systems take steps to implement the Stage 1 Disinfectants and Disinfection Byproducts Rule. The USEPA believes that the rule will generally track the approaches in the Interim Enhanced Surface Water Treatment Rule for improved turbidity control, including individual filter monitoring and reporting. The rule also addresses disinfection profiling and benchmarking. The USEPA is considering what modifications of some large system requirements may be appropriate for small systems. Long-Term 2 Enhanced Surface Water Treatment Rule The 1996 SDWA amendments required the USEPA to finalize a Stage 2 Disinfectants and Disinfection Byproducts Rule by 2002. Although the amendments did not require the USEPA to

finalize a Long-Term 2 Enhanced Surface Water Treatment Rule along with the Stage 2 Disinfectants and Disinfection Byproducts Rule, the USEPA believed that finalizing these rules together to ensure a proper balance between microbial and DBP risks was important. The intent of the rules is to provide additional public health protection (if needed) from DBPs and microbial pathogens. Ground Water Rule The USEPA published the Ground Water Rule in the Federal Register on November 8, 2006. The purpose of the rule is to provide for increased protection against microbial pathogens in public water systems that use groundwater sources. The USEPA is particularly concerned about groundwater systems that are susceptible to fecal contamination because disease-causing pathogens may be found in fecal contamination. The Ground Water Rule specifies the appropriate use of disinfection and, equally importantly, addresses other components of groundwater systems to ensure public health protection. More than 158,000 public or community water systems serve almost 89 million people through groundwater systems. Of these, 99% serve fewer than 10,000 people; however, systems serving more than 10,000 people serve 55% (more than 60 million) of all people who get their drinking water from public groundwater systems. Filter Backwash Recycling Rule The 1996 SDWA amendments required the USEPA to establish a standard on recycling filter backwash within the treatment process of public water systems by August 2000. The actual Filter Backwash Recycling Rule (FBRR) was implemented in 2001. The purpose of the FBRR is to improve public health protection by assessing and changing, where needed, recycle practices for improved contaminant control, particularly microbial contaminants. Generally, the FBRR requires systems that recycle to return specific recycle flows through all processes of the system's existing conventional or direct filtration system or at an alternate location approved by the state. The FBRR applies to public water systems that use surface water or groundwater under the direct influence of surface water, practice conventional or direct filtration, and recycle spent filter backwash, thickener supernatant, or liquids from dewatering processes. Note: This section has provided only a summary of federal drinking water requirements; to ensure full compliance, consult the federal regulations at 40 CFR 141 and any approved state requirements.

Opportunities for Public Involvement The USEPA encourages public input into regulation development. Public meetings and opportunities for public comment on MDBP rules are announced in the Federal Register. The USEPA's Office of Groundwater and Drinking Water also provides information regarding the MDBP rule and other programs online (www.epa.gov/safewater/standards.html). flocculants In addition to chlorine and sometimes fluoride, water treatment plants often add several other chemicals, including flocculants, to improve the efficiency of the treatment process—and they all add to the cocktail mix. Flocculants are chemical substances added to water to make particles clump together, which improves the effectiveness of filtration. Some of the most common flocculants are polyelectrolytes (polymers)—chemicals with constituents that cause cancer and birth defects and are banned for use by several countries. Although the USEPA classifies them as “probable human carcinogens,” it still allows their continued use. Acrylamide and epichlorohydrin are two flocculants used in the United States that are known to be associated with probable cancer risk (Lewis, 1996).

GROUNDWATER CONTAMINATION Groundwater under the direct influence of surface water comes under the same monitoring regulations as does surface water (i.e., all water open to the atmosphere and subject to surface runoff). The legal definition of groundwater under the direct influence of surface water is any water beneath the surface of the ground with (1) significant occurrence of insects or microorganisms, algae, or large-diameter pathogens such as *Giardia lamblia*; or (2) significant and relatively rapid

shifts in water characteristics such as turbidity, temperature, conductivity, or pH, which closely correlate to climatological or surface water conditions. Direct influence must be determined for individual sources in accordance with criteria established by the state. The state determines for individual sources in accordance with criteria established by the state, and that determination may be based on site-specific measurements of water quality and/or documentation of well construction characteristics and geology with field evaluation. Generally, most groundwater supplies in the United States are of good quality and produce essential quantities. The full magnitude of groundwater contamination in the United States is, however, not fully documented, and federal, state, and local efforts continue to assess and address the problems. Groundwater supplies about 25% of the freshwater used for all purposes in the United States, including irrigation, industrial uses, and drinking water (about 50% of the U.S. population relies on groundwater for drinking water). Elsewhere, groundwater aquifers beneath or close to Mexico City have provided the area with as much as 3 billion liters of water per day (Chilton, 1998). But, as groundwater pumping increases to meet water demand, it can exceed the aquifer rate of replenishment, and in many urban aquifers water levels are showing a long-term decline. Mexico City, for example, is sinking (Kimmelman, 2017). With excessive extraction comes a variety of other undesirable effects, including

- Increased pumping costs
- Changes in hydraulic pressure and underground flow directions (in coastal areas, this results in seawater intrusion)
- Saline water drawn up from deeper geological formations
- Poor-quality water from polluted shallow aquifers leaking downward

Severe depletion of groundwater resources is often compounded by a serious deterioration in its quality. Without a doubt, then, contamination of a groundwater supply should be a concern of those drinking water practitioners responsible for supplying a community with potable water provided by groundwater. Despite our strong reliance on groundwater, groundwater has for many years been one of the most neglected natural resources. Why? Good question. Groundwater has been ignored because it is less visible than other environmental resources—rivers or lakes, for example. What the public cannot see or observe, the public doesn't worry about, or even think about; however, recent publicity about events concerning groundwater contamination is making the public more aware of the problem, and the regulators have also taken notice. Are natural contaminants a threat to human health—harbingers of serious groundwater pollution events? No, not really. The main problem with respect to serious groundwater pollution has been human activities. When we improperly dispose of wastes or spill hazardous substances onto the ground, we threaten our groundwater and in turn public health. Let's take a closer look at a few sources of groundwater contamination. Several sources of groundwater contamination are cause for concern for the drinking water practitioner. Consider for a moment the importance of groundwater. People depend on groundwater in every state, and its usage accounts for approximately one-fourth of all water used. This consumption includes about 35% of water withdrawn for municipal water supplies.

unDergrounD storage tanks If we could look at a map of the United States indicating the exact location of every underground storage tank (UST), most of us would be surprised at the large number of tanks buried underground. With so many buried tanks, it should come as no surprise that structural failures arising from a wide variety of causes have occurred over the years. Subsequent leaking has become a huge source of contamination that affects the quality of local groundwaters.

Note: A UST is a tank and any underground piping connected to the tank that has at least 10% of its combined volume below ground (USEPA, 2017).

The fact is, leakage of petroleum and its products from USTs occurs more often than we generally realize. This widespread problem has been and continues to be a major concern and priority in the United States. In 1987, the USEPA promulgated regulations for many of the nation's USTs, and much progress has been made in mitigating this problem to date. When a UST leak or past leak is discovered and contaminants have been or are being released to the soil and thus to groundwater, it would seem to be a rather straightforward process to identify the contaminant, which in many cases would be fuel oil, diesel, or gasoline. Other contaminants, however, also present problems; for example, in the following section, we discuss one such contaminant, a byproduct of gasoline, to help illustrate the magnitude of leaking USTs. mtbe and ethanol

In 1997, the USEPA issued a drinking water advisory, Consumer Acceptability Advice and Health Effects Analysis on Methyl Tertiary-Butyl Ether (MtBE), for communities exposed to drinking water contaminated with MtBE, a volatile organic chemical. MtBE was used as an octane enhancer in gasoline because it can promote more complete burning of gasoline (thus reducing carbon monoxide and ozone levels). Note: A USEPA Advisory is usually initiated to provide information and guidance to individuals or agencies concerned with potential risk from drinking water contaminants for which no national regulations currently exist. Advisories are not mandatory standards for action and are used only for guidance. They are not legally enforceable, and are subject to revision as new information becomes available. The USEPA's Health Advisory program is recognized in the 1996 amendments to the Safe Drinking Water Act, which state in Section 102(b)(1)(F): The Administrator may publish health advisories (which are not regulations) or take other appropriate actions for contaminants not subject to any national primary drinking water regulation. As its title indicates, this Advisory includes consumer acceptability advice as "appropriate" under this statutory provision, as well as a health effects analysis. The Clean Air Act of 1990 mandated the use of reformulated gasoline (RFG) in areas of the country with the worst ozone or smog problems. After passage of the Clean Air Act, RFG was required to meet certain technical specifications set forth in the Act, including a specific oxygen content. Ethanol and MtBE were the primary oxygenates used to meet the oxygen content requirement. In 2005, the Energy Policy Act removed the oxygenate requirement for RFG, and Congress instituted a renewable fuel standard. In response, refiners made a wholesale switch, removing MtBE and blending fuel instead with ethanol. According to USEPA survey data, MtBE has not been used in significant quantities in RFG areas since 2005. A similar decrease in MtBE use has also been observed in conventional gasoline areas (USEPA, 2016). Studies identified significant air quality and public health benefits that were a direct result of the use of fuels oxygenated with MtBE, ethanol, or other chemicals. Refiners' fuel data submitted to the USEPA for 1995/1996, for example, indicated that the national emissions benefits exceeded those required. The 1996 Air Quality Trends Report showed that toxic air pollutants declined significantly between 1994 and 1995, and analysis indicated that at least some of this progress could be attributed to the use of RFG. Beginning in the year 2000, required emission reductions became substantially greater, at about 27% for volatile organic chemicals, 22% for toxic air pollutants, and 7% for nitrogen oxides. Note: When gasoline that has been oxygenated with MtBE comes in contact with water, large amounts of MtBE dissolve. At 25°C, the water solubility of MtBE is about 5000 mg/L for a gasoline that is 10% MtBE by weight. In contrast, for a nonoxygenated gasoline, the total hydrocarbon solubility in water is typically about 120 mg/L. MtBE sorbs only weakly to soil and aquifer material; therefore, sorption will not significantly retard MtBE transport by groundwater. In addition, the compound generally resists degradation in groundwater (Squillace et al.,

1997). A limited number of instances of significant contamination of drinking water with MtBE have occurred because of leaks from underground and aboveground petroleum storage tank systems and pipelines. Due to its small molecular size and solubility in water, MtBE moves rapidly into groundwater, faster than do other constituents of gasoline. Public and private wells have been contaminated in this manner. Non-point sources (such as recreational watercraft) are most likely to be the cause of small amounts of contamination in a large number of shallow aquifers and surface waters. Air deposition through precipitation of industrial or vehicular emissions may also contribute to surface water contamination. The extent of any potential for build-up in the environment from such deposition is uncertain. Based on the limited sampling data available, most concentrations at which MtBE has been found in drinking water sources are unlikely to cause adverse health effects; however, the USEPA is continuing to evaluate the available information and is doing additional research to seek more definitive estimates of potential risks to humans from drinking water. There are no data on the effects on humans of drinking MtBE-contaminated water. In laboratory tests on animals, cancer and noncancer effects have occurred at high levels of exposure. These tests are conducted by inhalation exposure or by introducing the chemical in oil directly to the stomach. The tests support a concern for potential human hazard; however, because the animals were not exposed through drinking water, significant uncertainties exist concerning the degree of risk associated with human exposure to low concentrations typically found in drinking water. The very unpleasant taste and odor of MtBE make contaminated drinking water unacceptable to the general public. Studies conducted on the concentrations of MtBE in drinking water determined the level at which individuals can detect the odor or taste of the chemical. Humans vary widely in the concentrations they are able to detect. Some who are sensitive can detect very low concentrations. Others do not taste or smell the chemical, even at much higher concentrations. The presence or absence of other natural or water treatment chemicals sometimes masks or reveals the taste or odor effects. Studies to date have not been extensive enough to completely describe the extent of this variability or to establish a population response threshold. Nevertheless, it can be concluded from the available studies that keeping concentrations in the range of 20 to 40 µg/L of water or below will likely avert unpleasant taste and odor effects, recognizing that some people may detect the chemical below this. The original USEPA Advisory recommended control levels for taste and odor acceptability that would also protect against potential health effects. Concentrations in the range of 20 to 40 µg/L are about 20,000 to 100,000 (or more) times lower than the range of exposure levels in which cancer or noncancer effects were observed in rodent tests. This margin of exposure lies within the range of margins of exposure typically provided to protect against cancer effects by the National Primary Drinking Water Regulations under the federal Safe Drinking Water Act—a margin greater than such standards typically provided to protect against noncancer effects. Protection of the water source from unpleasant taste and odor as recommended also protects consumers from potential health effects. The USEPA observed that occurrences of groundwater contamination at or above this 20 to 40-µg/L taste and odor threshold (that is, contamination at levels that may create consumer acceptability problems for water supplies) have, to date, resulted from leaks in petroleum storage tanks or pipelines, not from any other sources. Public water systems that conduct routine monitoring for volatile organic chemicals can test for MtBE at little additional cost, and some states are already moving in this direction. Public water systems detecting MtBE in their source water at problematic concentrations can remove MtBE from water using the same conventional treatment techniques that are used to clean up other contaminants originating from gasoline

releases—air stripping and granular activated carbon (GAC), for example. Because MtBE is more soluble in water and more resistant to biodegradation than other chemical constituents in gasoline, air stripping and GAC treatment require additional optimization and must often be used together to effectively remove MtBE from water. The costs of removing MtBE are higher than when treating for gasoline releases that do not contain MtBE. Oxidation of MtBE using ultraviolet/peroxide/ ozone treatment may also be feasible but typically has higher capital and operating costs than air stripping and GAC. Note: The U.S. Geological Survey analyzed 3500 water samples collected from various types of wells from 1985 to 2001 to assess the presence of 55 volatile organic chemicals in groundwater. Trihalomethanes, which may originate as chlorination byproducts, and solvents were the most frequently detected VOCs, but MtBE demonstrated regional patterns of occurrence (Zogorski et al., 2006).

Industrial Waste Because industrial waste represents a significant source of groundwater contamination, drinking water practitioners and others expend an increasing amount of time in abating or mitigating pollution events that damage groundwater supplies. Groundwater contamination from industrial waste usually begins with the practice of disposing of industrial chemical wastes in surface impoundments—unlined landfills or lagoons, for example. Fortunately, these practices, for the most part, are part of our past. Today, we know better; for example, we now know that what is most expedient or least expensive does not work for industrial waste disposal practices. We have found through actual experience that the long run has proven just the opposite—for society as a whole (with respect to health hazards and the costs of cleanup activities) to ensure clean or unpolluted groundwater supplies is very expensive and utterly necessary.

septic tanks Seepage from septic tanks is a biodegradable waste capable of affecting the environment through water and air pollution. The potential environmental problems associated with use of septic tanks are magnified when you consider that subsurface sewage disposal systems (septic tanks) are used by almost one-third of the U.S. population. Briefly, a septic tank and leaching field system traps and stores solids while the liquid effluent flows from the tank into a leaching or absorption field, where it slowly seeps into the soil and degrades naturally. The problem with subsurface sewage disposal systems such as septic tanks is that most of the billions of gallons of sewage that enter the ground each year are not properly treated. Because of faulty construction or lack of maintenance, not all of these systems work properly. Experience has shown that septic disposal systems are frequently sources of fecal bacteria and virus contamination of water supplies taken from private wells. Many septic tank owners dispose of detergents, nitrates, chlorides, and solvents in their septic systems or use solvents to treat their sewage waste. A septic tank cleaning fluid that is commonly used contains organic solvents (trichloroethylene, or TCE) that are potential human carcinogens that pollute the groundwater in areas served by septic systems.

landfills Humans have been disposing of waste by burying it in the ground since time immemorial. In the past, this practice was largely uncontrolled, and the disposal sites (i.e., garbage dumps) were places where municipal solid wastes were simply dumped on and into the ground without much thought or concern. Even in this modern age, landfills have been used to dispose of trash and waste products at controlled locations that are then sealed and buried under the ground. Now such practices are increasingly seen as a less than satisfactory disposal method, because of the long-term environmental impact of waste materials in the ground and groundwater. Unfortunately, many of the older (and even some of the newer) sites have been located in low-lying areas with high groundwater tables. Leachate (seepage of liquid through

the waste) high in biochemical oxygen demand (BOD), chloride, organics, heavy metals, nitrate, and other contaminants has little difficulty reaching the groundwater in such disposal sites. In the United States, literally thousands of inactive or abandoned dumps like this exist.

agriculture Fertilizers and pesticides are the two most significant groundwater contaminants that result from agricultural activities. The impact of agricultural practices wherein fertilizers and pesticides are normally used is dependent on local soil conditions. If, for example, the soil is sandy, nitrates from fertilizers are easily carried through the porous soil into the groundwater, contaminating private wells. Pesticide contamination of groundwater is a subject of national importance because groundwater is used for drinking water by about 50% of the nation's population. This especially concerns people living in the agricultural areas where pesticides are most often used, as about 95% of that population relies upon groundwater for drinking water. Before the mid1970s, the common thought was that soil acted as a protective filter, one that stopped pesticides from reaching groundwater. Studies have now shown that this is not the case.

Pesticides can reach water-bearing aquifers below ground from applications onto crop fields, seepage of contaminated surface water, accidental spills and leaks, improper disposal, and even through injection of waste material into wells. Pesticides are mostly modern chemicals. Many hundreds of these compounds are used, and extensive tests and studies of their effect on humans have not been completed. This leads us to ask, "Just how concerned should we be about their presence in our drinking water?" Certainly, considering pesticides to be potentially dangerous and handling them with appropriate care would be wise.

We can say they pose a potential danger if they are consumed in large quantities, but as any experienced scientist knows we cannot draw factual conclusions unless scientific tests have been done. Some pesticides have had a designated maximum contaminant level (MCL) in drinking water set by the USEPA, but many have not. Another serious point to consider is the potential effect of combining more than one pesticide in drinking water, the effects of which might be different than those of each individual pesticide alone. This is another situation where we do not have sufficient scientific data to draw reliable conclusions—in other words, we don't know what we don't know.

saltWater intrusion In many coastal cities and towns as well as in island locations, the intrusion of salty seawater presents a serious water quality problem. Because freshwater is lighter than saltwater (the specific gravity of seawater is about 1.025), it will usually float above a layer of saltwater. When an aquifer in a coastal area is pumped, the original equilibrium is disturbed and saltwater replaces the freshwater (Viessman and Hammer, 1998). The problem is compounded by increasing population, urbanization, and industrialization, all of which increase the use of groundwater supplies. In such areas, while groundwater is heavily drawn upon, the quantity of natural groundwater recharge is decreased because of the construction of roads, tarmac, and parking lots, which prevent rainwater from infiltrating, reducing the groundwater table elevation. In coastal areas, the natural interface between the fresh groundwater flowing from upland areas and the saline water from the sea is constantly under attack by human activities. Because seawater is approximately 2.5 times more dense than freshwater, a high-pressure head of seawater occurs (in relation to freshwater), which results in a significant rise in the seawater boundary. Potable water wells close to this rise in sea level may have to be abandoned because of saltwater intrusion.

other sources of groundWater contamination To this point, we have discussed only a few of the many sources of groundwater contamination; for example, we have not discussed mining and petroleum activities that lead to contamination of groundwater or contamination caused by activities in urban areas, both

of which are important. Urban activities (including spreading salt on roads to keep them free of ice during the winter) eventually contribute to contamination of groundwater supplies, as can underground injection wells used to dispose of hazardous materials. As discussed earlier, underground storage tanks are also significant contributors to groundwater pollution. Other sources of groundwater contamination include the following items on our short list:

• Waste tailings • Residential disposal • Urban runoff • Hog wastes • Biosolids • Land-applied wastewater • Graveyards • Deicing salts • Surface impoundments • Waste piles • Animal feeding operations • Natural leaching • Animal burial • Mine drainage • Pipelines • Open dumps • Open burning • Atmospheric pollutants • Hydraulic fracturing

Raw sewage is not listed, because for the most part raw sewage is no longer routinely dumped into our nation's wells or into our soil. Sewage treatment plants effectively treat wastewater so that it can be safely discharged to local water bodies. In fact, the amount of pollution being discharged from these plants has been cut by over one-third during the past several decades, even as the number of people served has doubled. Yet, in some areas raw sewage spills still occur, sometimes because a underground sewer line is blocked, broken, or too small or because periods of heavy rainfall overload the capacity of the sewer line or sewage treatment plant so overflows into city streets or streams occur. Some of this sewage finds its way to groundwater supplies.

SUMMARY The best way to prevent groundwater pollution is to stop it from occurring in the first place. Unfortunately, a perception held by many is that natural purification of chemically contaminated ground can take place on its own—without the aid of human intervention. To a degree this is true; however, natural purification functions on its own time, not on human time. Natural purification could take decades, perhaps centuries. The alternative? Remediation. But remediation and mitigation don't come cheap. When groundwater is contaminated, the cleanup efforts are sometimes much too expensive to be practical. The USEPA established the Groundwater Guardian program in 1994, which is a voluntary approach to improving drinking water safety. Established and managed by a nonprofit organization in the Midwest and strongly promoted by the USEPA, this program focuses on communities that rely on groundwater for their drinking water. It provides special recognition and technical assistance to help communities protect their groundwater from contamination. Groundwater Guardian programs have been established in over 150 communities in 34 states (<http://www.groundwater.org>).

Drinking Water Monitoring INTRODUCTION Drinking water monitoring refers to water quality monitoring based on three criteria: 1. Ensure to the greatest extent possible that the water is not a danger to public health. 2. Ensure that water provided at the tap is as aesthetically pleasing as possible. 3. Ensure compliance with applicable regulations. To meet these goals, all public water systems must monitor water quality to some extent. Before the Ground Water Rule of 2006 was implemented, the degree of monitoring employed was dependent on local needs, requirements, and the type of water system. Small water systems using good-quality water from deep wells may only have to provide occasional monitoring, but systems using surface water sources must test water quality frequently (AWWA, 2003). The Ground Water Rule modified sampling and monitoring requirements for all public water systems that use groundwater sources at risk of microbial contamination; they are now required to take corrective action to protect consumers from harmful bacteria and viruses. Monitoring is a key element of this risk-targeted approach.

Note: Compliance monitoring ensures that systems already providing 99.99% (4-log) inactivation, removal,

or a state-approved combination of inactivation and removal of viruses are achieving this level of treatment. Water quality monitoring can be defined as the sampling and analysis of water constituents and conditions. When we monitor, we collect data. As a monitoring program is developed, deciding the reason for collecting the information is important. The reasons for gathering it are defined by establishing a set of objectives and providing a description of who will collect the information. It may come as a surprise to learn that today the majority of people collecting data are volunteers, not necessarily professional drinking water practitioners. These volunteers have a vested interest in their local stream, lake, or other body of water and in many cases are proving they can successfully carry out a water quality monitoring program. IS THE WATER GOOD OR BAD?*

To answer the question of whether the water is good or bad we must consider two factors. First, let's return to the basic principles of water quality monitoring—sampling and analyzing water constituents and conditions. These constituents include the following:

1. Introduced pollutants, such as pesticides, metals, and oil
2. Constituents found naturally in water that can nevertheless be affected by human sources, such as dissolved oxygen, bacteria, and nutrients

The magnitude of their effects is influenced by properties such as pH and temperature; for example, temperature influences the quantity of dissolved oxygen that water is able to contain, and pH affects the toxicity of ammonia. The second factor to be considered is that the only valid way to answer this question is to conduct tests, the results of which must then be compared to some form of water quality standards. If simply assigning a “good” and “bad” value to each test factor were possible, the meters and measuring devices in water quality test kits would be much easier to make. Instead of fine graduations, they could simply have a “good” and a “bad” zone. Water quality—the difference between good and bad water—must be interpreted according to the intended use of the water; for example, the perfect balance of water chemistry that provides a sparkling clear, sanitary swimming pool would not be acceptable for drinking water and would be a deadly environment for many biota (Table 10.1). In another example, widely different levels of fecal coliform bacteria are considered acceptable, depending on the intended use of the water. State and local water quality practitioners as well as volunteers have been monitoring water quality conditions for many years. In fact, until the past decade or so (until biological monitoring protocols were developed and began to take hold), water quality monitoring was generally considered the primary way to identify water pollution problems. Today, professional water quality practitioners and volunteer program coordinators alike are moving toward approaches that combine chemical, physical, and biological monitoring methods to achieve the best picture of water quality conditions. Water quality monitoring can be used for many purposes:

1. To identify whether waters are meeting designated uses. All states have established specific criteria (limits on pollutants) identifying what concentrations of chemical pollutants are allowable in their waters. When chemical pollutants exceed maximum or minimum allowable concentrations, waters may no longer be able to support the beneficial uses—such as fishing, swimming, and drinking—for which they have been designated (see Table 10.2). Designated or intended uses and the specific criteria that protect them (along with antidegradation statements prohibiting waters from deteriorating below existing or anticipated uses) together form water quality standards. State water qual-

ity professionals assess water quality by comparing the concentrations of chemical pollutants found in streams to the criteria in the state's standards and so judge whether or not streams are meeting their designated uses. Water quality monitoring, however, might be inadequate for determining whether aquatic life needs are being met in a stream. Although some constituents (such as dissolved oxygen and temperature) are important to maintaining healthy fish and aquatic insect populations, other factors (such as the physical structure of the stream and the condition of the habitat) play an equal or greater role. Biological monitoring methods are generally better suited to determining whether aquatic life is supported.

2. To identify specific pollutants and sources of pollution. Water quality monitoring helps link sources of pollution to water body quality problems because it identifies specific problem pollutants. Because certain activities tend to generate certain pollutants (bacteria and nutrients are more likely to come from an animal feedlot than an automotive repair shop), a tentative link to what would warrant further investigation or monitoring can be formed.
3. To determine trends. Chemical constituents that are properly monitored (i.e., using consistent time of day and on a regular basis using consistent methods) can be analyzed for trends over time.
4. To screen for impairment. Finding excessive levels of one or more chemical constituents can serve as an early warning for potential pollution problems.

state Water Quality stanDarDs programs Each state has a program to set standards for the protection of each body of water within its boundaries. Standards for each body of water are developed that 1. Depend on the water's designated use 2. Are based on USEPA national water quality criteria and other scientific research into the effects of specific pollutants on different types of aquatic life and on human health 3. May include limits based on the biological diversity of the body of water (the presence of food and prey species) State water quality standards set limits on pollutants and establish water quality levels that must be maintained for each type of water body, based on its designated use. Resources for this type of information include the following: 1. USEPA water quality criteria program 2. U.S. Fish and Wildlife Service habitat suitability index models (for specific species of local interest) Individual monitoring test results can be plotted against these standards to provide a focused, relevant, required assessment of water quality.

DESIGNING A WATER QUALITY MONITORING PROGRAM The first step in designing a water quality monitoring program is to determine the purpose for the monitoring. This aids in selection of parameters to monitor. This decision should be based on such factors as Types of water quality problems and pollution sources that are likely to be encountered (see Table 10.3) 1. Cost of available monitoring equipment 2. Precision and accuracy of available monitoring equipment 3. Capabilities of monitors

This discussion in this chapter focuses on the parameters most commonly monitored by drinking water practitioners in streams (i.e., it is assumed, for illustration and discussion purposes, that the water source is a surface water stream). These parameters include dissolved oxygen (DO), biochemical oxygen demand (BOD), temperature, hardness, pH, turbidity, orthophosphates, nitrates, total solids, conductivity, total alkalinity, fecal bacteria, apparent color, and odor (see Figure 10.1). Note: When monitoring water supplies under the Safe Drinking Water Act (SDWA) or the National Pollutant Discharge Elimination System (NPDES), utilities must follow USEPA-approved test procedures. Additional testing requirements for

these and other federal programs are published as amendments in the Federal Register. Except when monitoring discharges for specific compliance purposes, a large number of approximate measurements can provide more useful information than one or two accurate analyses. Because water quality and chemistry continually change, making periodic, representative measurements and observations that indicate the range of water quality is necessary, rather than testing the quality at any single moment. The more complex a water system, the more time is required to observe, understand, and draw conclusions regarding the cause and effect of changes in the particular system.

GENERAL PREPARATION AND SAMPLING CONSIDERATIONS The sections that follow detail specific and equipment considerations and analytical procedures for each of the most common water quality parameters, and general tasks that should be accomplished any time water samples are taken are discussed below.

preparation of sampling containers Sampling devices should be corrosion resistant, easily cleaned, and capable of collecting desired samples safely and in accordance with test requirements. Whenever possible, assign a sampling device to each sampling point. Sampling equipment must be cleaned on a regular schedule to avoid contamination. Note: Some tests require special equipment to ensure that the sample is representative. Dissolved oxygen and fecal bacteria sampling requires special equipment and procedures to prevent collection of nonrepresentative samples.

Reused sample containers and glassware must be cleaned and rinsed before the first sampling run and after each run by following Method A or Method B described below. The more suitable method depends on the parameter being measured.

Method A: General Preparation of Sampling Containers Use the following method when preparing all sample containers and glassware for monitoring conductivity, total solids, turbidity, pH, and total alkalinity.

Wearing latex gloves,

1. Wash each sample bottle or piece of glassware with a brush and phosphatefree detergent.
2. Rinse three times with cold tap water.
3. Rinse three times with distilled or deionized water.

Method B: Acid Wash Procedures Use this method when preparing all sample containers and glassware for monitoring nitrates and phosphorus. Wearing latex gloves,

1. Wash each sample bottle or piece of glassware with a brush and phosphatefree detergent.
2. Rinse three times with cold tap water.
3. Rinse with 10% hydrochloric acid.
4. Rinse three times with deionized water.

Sample Types Two basic types of samples are commonly used for water quality testing: grab samples and composite samples. The type of sample used depends on the specific test, the reason why the sample is being collected, and the applicable regulatory requirements. Grab samples are collected at one time and one location. They are representative only of the conditions at the time of collection. Grab samples must be used to determine pH, total residual chlorine (TRC), dissolved oxygen, and fecal coliform concentrations.

Grab samples may also be used for any test that does not specifically prohibit their use. Composite samples consist of a series of individual grab samples collected over a specified period of time in proportion to flow. The individual grab samples are mixed together in proportion to the flow rate at the time the sample was collected to form the composite sample. Note: Before collecting samples for any test procedure, it is best to review the sampling requirements of the test.

collecting samples from a stream In general, sample away from the stream bank in the main current. Never sample stagnant water. The outside curve of the stream is often a good place to sample, because the main current tends to hug this bank. In shallow stretches, carefully wade into the center current to collect the sample. A boat is required for deep sites. Try to maneuver the boat into the center of the main current to collect the water sample. When collecting a water sample for analysis in the field or at the lab, follow the procedures provided below.

Whirl-Pak® Bags 1. Label the bag with the site number, date, and time. 2. Tear off the top of the bag along the perforation above the wire tab just before sampling. Avoid touching the inside of the bag. If you accidentally touch the inside of the bag, use another one. 3. When wading, try to disturb as little bottom sediment as possible. In any case, be careful not to collect water that contains bottom sediment. Stand facing upstream. Collect the water samples in front of you. By boat, carefully reach over the side and collect the water sample on the upstream side of the boat. 4. Hold the two white pull-tabs in each hand and lower the bag into the water on your upstream side with the opening facing upstream. Open the bag midway, between the surface and the bottom by pulling the white pull-tabs. The bag should begin to fill with water. You may need to scoop water into the bag by drawing it through the water upstream and away from you. Fill the bag no more than three-quarters full. 5. Lift the bag out of the water. Pour out excess water. Pull on the wire tabs to close the bag. Continue holding the wire tabs and flip the bag over at least four to five times quickly to seal the bag. Do not try to squeeze the air out of the top of the bag. Fold the ends of the bag, being careful not to puncture the bag. Twist them together, forming a loop. 6. Fill in the bag number and site number on the appropriate field data sheet. This is important. It is the only way the lab specialist will know which bag goes with which site. 7. If samples are to be analyzed in a lab, place the sample in the cooler with ice or cold packs. Take all samples to the lab.

Screw-Cap Bottles To collect water samples using screw-cap bottles, use the following procedures (see Figure 10.2):

1. Label the bottle with the site number, date, and time.
2. Remove the cap from the bottle just before sampling. Avoid touching the inside of the bottle or the cap. If you accidentally touch the inside of the bottle, use another one.
3. When wading, try to disturb as little bottom sediment as possible. In any case, be careful not to collect water that has sediment from bottom disturbance. Stand facing upstream. Collect the water sample on your upstream side, in front of you. You may also tape the bottle to an extension pole to sample from deeper water. By boat, carefully reach over the side and collect the water sample on the upstream side of the boat.
4. Hold the bottle near its base and plunge it (opening downward) below the water surface. If you are using an extension pole, remove the cap, turn the bottle upside down, and plunge it into the water,

facing upstream. Collect a water sample 8 to 12 inches beneath the surface, or midway between the surface and the bottom if the stream reach is shallow.

5. Turn the bottle underwater into the current and away from you. In slowmoving stream reaches, push the bottle underneath the surface and away from you in the upstream direction.
6. Leave a 1-inch air space (except for DO and BOD samples). Do not fill the bottle completely (so the sample can be shaken just before analysis). Recap the bottle carefully, remembering not to touch the inside.
7. Fill in the bottle number and site number on the appropriate field data sheet. This is important because it tells the lab specialist which bottle goes with which site.
8. If the samples are to be analyzed in the lab, place them in the cooler for transport to the lab.

sample preservation and storage Samples can change very rapidly, and no single preservation method will serve for all samples and constituents. If analysis must be delayed, follow the instructions for sample preservation and storage listed in *Standard Methods for the Examination of Water and Wastewater* (APHA-AWWA-WEF, 2017), or those specified by the laboratory that will eventually process the samples (see Table 10.4). In general, handle the sample in a way that does not cause changes in biological activity, physical alterations, or chemical reactions. Cool the sample to reduce biological and chemical reactions. Store in darkness to suspend photosynthesis. Fill the sample container completely to prevent the loss of dissolved gases. Be aware that metal cations such as iron and lead and suspended particles may adsorb onto container surfaces during storage. References used for sampling and testing must correspond to those listed in the most current federal regulations. For the majority of tests, to compare the results of either different water quality monitors or the same monitors over the course of time requires some form of standardization of the methods. The American Public Health Association (APHA) recognized this requirement when, in 1899, it appointed a committee to draw up standard procedures for the analysis of water. The report (published in 1905) constituted the first edition of what is now known as *Standard Methods for the Examination of Water and Wastewater*, or *Standard Methods*. This book serves as the primary reference for water testing methods and as the basis for most USEPA-approved methods. This book is now in its 23rd edition and serves as the primary reference for water testing methods, and as the basis for most USEPA-approved methods. **TEST METHODS*** Descriptions of general methods to help you understand how each works in specific test kits follow. Always follow the specific instructions included with the equipment and individual test kits. Most water analyses are conducted either by titrimetric analyses or colorimetric analyses. Both methods are easy to use and provide accurate results.

titrimetric Titrimetric analyses are based on adding a solution of known strength (the titrant) to a specific volume of a treated sample in the presence of an indicator. The indicator produces a color change indicating that the reaction is complete. Titrants are generally added by a titrator (microburette) or a precise glass pipette.

colorimetric Two basic types of colorimetric tests are commonly used: 1. The pH is a measure of the concentration of hydrogen ions (the acidity of a solution) determined by the reaction of an indicator that varies in color, depending on the hydrogen ion levels in the water. 2. Tests that determine a concentra-

tion of an element or compound are based on Beer's law. Simply, this law states that the higher the concentration of a substance, the darker the color produced in the test reaction and therefore the more light absorbed. Assuming a constant viewpath, the absorption increases exponentially with concentration.

Visual methods The Octet Comparator uses standards that are mounted in a plastic comparator block. It employs eight permanent translucent color standards and built-in filters to eliminate optical distortion. The sample is compared using either of two viewing windows. Two devices that can be used with the comparator are a color reader, which neutralizes color or turbidity in water samples, and an axial mirror, which intensifies faint colors of low concentrations for easy distinction.

electronic methods Although the human eye is capable of differentiating color intensity, interpretation is quite subjective. Electronic colorimeters consist of a light source that passes through a sample and is measured on a photodetector with an analog or digital readout. Besides electronic colorimeters, specific electronic instruments are manufactured for lab and field determination of many water quality factors, including pH, total dissolved solids, conductivity, dissolved oxygen, temperature, and turbidity.

DISSOLVED OXYGEN AND BIOCHEMICAL OXYGEN DEMAND* A stream system (in this case, the hypothetical one providing the source of water used for this discussion) produces and consumes oxygen. It gains oxygen from the atmosphere and from plants as a result of photosynthesis. Because of running water's churning, it dissolves more oxygen than still water—in a reservoir behind a dam, for example. Respiration by aquatic animals, decomposition, and various chemical reactions consume oxygen. Oxygen is actually poorly soluble in water. Its solubility is related to pressure and temperature. In water supply systems, dissolved oxygen (DO) in raw water is considered the necessary element to support life of many aquatic organisms. From the drinking water practitioner's point of view, DO is an important indicator of the water treatment process and an important factor in corrosivity. Wastewater from sewage treatment plants often contains organic materials that are decomposed by microorganisms, which use oxygen in the process. The amount of oxygen consumed by these organisms in breaking down the waste is known as the biochemical oxygen demand (BOD). We include a discussion of BOD and how to monitor it later. Other sources of oxygen-consuming waste include stormwater runoff from farmland or urban streets, feedlots, and failing septic systems. Oxygen is measured in its dissolved form as dissolved oxygen. If more oxygen is consumed than produced, DO levels decline and some sensitive animals may move away, weaken, or die. DO levels fluctuate over a 24-hour period and seasonally. They vary with water temperature and altitude. Cold water holds more oxygen than warm water (Table 10.5), and water holds less oxygen at higher altitudes. Thermal discharges (such as water used to cool machinery in a manufacturing plant or a power plant) raise the temperature of water and lower its oxygen content. Aquatic animals are most vulnerable to lowered DO levels in the early morning on hot summer days when stream flows are low, water temperatures are high, and aquatic plants have not been producing oxygen since sunset.

sampling and Equipment considerations In contrast to lakes, where dissolved oxygen levels are most likely to vary vertically in the water column, changes in DO in rivers and streams move horizontally along the course of the waterway. This is especially true in smaller, shallow streams. In larger, deeper rivers, some vertical stratification of dissolved oxygen might occur. The DO levels in and below riffle areas, waterfalls, or dam spillways are typically higher than those in pools and slower moving stretches. If we want to measure the effect of a dam, sampling for DO behind the dam immediately below the spillway and upstream of the dam would be important. Because DO levels are critical to fish, a good place to sample is in the

pools that fish tend to favor or in the spawning areas they use. An hourly time profile of DO levels at a sampling site is a valuable set of data, because it shows the change in DO levels from the low point (just before sunrise) to the high point (sometime near midday); however, this might not be practical for a volunteer monitoring program. Note the time of the DO sampling to help judge when in the daily cycle the data were collected. Dissolved oxygen is measured in either milligrams per liter (mg/L) or as percent saturation. Milligrams per liter is the amount of oxygen in a liter of water. Percent saturation is the amount of oxygen in a liter of water relative to the total amount of oxygen that the water can hold at that temperature. DO samples are collected using

a special BOD bottle: a glass bottle with a “turtleneck” and a ground glass stopper. You can fill the bottle directly in the stream if the stream is wadeable or boatable, or you can use a sampler dropped from a bridge or boat into water deep enough to submerge the sampler. Samplers can be made or purchased. Dissolved oxygen is measured primarily either by using some variation of the Winkler method or by using a meter and probe.

Winkler Method The Winkler method involves filling a sample bottle completely with water (no air is left to bias the test). The dissolved oxygen is then fixed using a series of reagents that form a titrated acid compound. Titration involves the drop-by-drop addition of a reagent that neutralizes the acid compound, causing a change in the color of the solution. The point at which the color changes is the endpoint and is equivalent to the amount of oxygen dissolved in the sample. The sample is usually fixed and titrated in the field at the sample site, but preparing the sample in the field and delivering it to a lab for titration is possible. Dissolved oxygen field kits using the Winkler method

are relatively inexpensive, especially compared to a meter and probe. Field kits run between \$35 and \$200, and each kit comes with enough reagents to run 50 to 100 DO tests. Replacement reagents are inexpensive and are available already measured out for each test in plastic pillows. The reagents can also be bought in larger quantities in bottles and measured out with a volumetric scoop. The advantage of the pillows is that they have a longer shelf life and are much less prone to contamination or spillage, but buying larger quantities in bottles has the advantage of considerably lower cost per test. The major factor in the expense of the kits is the method of titration used—eyedropper, syringe-type titrator, or digital titrator. Eyedropper and syringe-type titration is less precise than digital titration, because a larger drop of titrant is allowed to pass through the dropper opening, and on a microscale the drop size (and thus the volume of titrant) can vary from drop to drop. A digital titrator or a burette (a long glass tube with a tapered tip like a pipette) permits much more precision and uniformity in the amount of titrant it allows to pass. If a high degree of accuracy and precision in DO results is required, a digital titrator should be used. A kit that uses an eye dropper or syringe type of titrator is suitable for most other purposes. The lower cost of this type of DO field kit might be attractive if several teams of samplers and testers at multiple sites at the same time are necessary.

Meter and Probe A dissolved oxygen meter is an electronic device that converts signals from a probe placed in the water into units of DO in milligrams per liter. Most meters and probes also measure temperature. The probe is filled with a salt solution and has a selectively permeable membrane that allows DO to pass from the stream water into the salt solution. The DO that has diffused into the salt solution changes the electric potential of the salt solution, and this change is sent by electric cable to the meter, which converts the signal to milligrams per liter on a scale that the volunteer can read. DO meters are expensive com-

pared to field kits that use the titration method. Meter and probe combinations run between \$500 and \$1200, including a long cable to connect the probe to the meter. The advantage of a meter and probe is that DO and temperature can be quickly read at any point where the probe is inserted into the stream; also, DO levels can be measured at a certain point on a continuous basis. The results are read directly as milligrams per liter, unlike the titration methods, where the final titration result might have to be converted by an equation to milligrams per liter. DO meters are more fragile than field kits, however, and repairs to a damaged meter can be costly. The meter and probe must be carefully maintained and must be calibrated before each sample run or, if many tests are done, between sampling. Because of the expense, a small waterworks might only have one meter and probe, which means that only one team of samplers can sample DO and they must test all the sites. With field kits, on the other hand, several teams can sample simultaneously. Laboratory Testing of Dissolved Oxygen If a meter and probe are used, the testing must be done in the field because dissolved oxygen levels in a sample bottle change quickly due to the decomposition of organic material by microorganisms or the production of oxygen by algae and other plants in the sample, which can lower the DO reading. If a variation of the Winkler method is used, it is possible to fix the sample in the field and then deliver it to a lab for titration. This might be preferable if sampling is conducted under adverse conditions or if time spent collecting samples is an issue. Titrating samples in the lab is a little easier, and greater quality control is possible because the same person can do all the titrations.

What is biochemical oxygen Demand and Why is it important? Biochemical oxygen demand (BOD) measures the amount of oxygen consumed by microorganisms in decomposing organic matter in stream water. BOD also measures the chemical oxidation of inorganic matter (the extraction of oxygen from water via chemical reaction). A test is used to measure the amount of oxygen consumed by these organisms during a specified period of time (usually 5 days at 20°C). The rate of oxygen consumption in a stream is affected by a number of variables: temperature, pH, the presence of certain kinds of microorganisms, and the type of organic and inorganic material in the water. BOD directly affects the amount of dissolved oxygen in rivers and streams. The greater the BOD, the more rapidly oxygen is depleted in the river or stream, leaving less oxygen available to higher forms of aquatic life. The consequences of high BOD are the same as those for low dissolved oxygen: Aquatic organisms become stressed, suffocate, and die. Most river waters used as water supplies have a BOD of less than 7 mg/L; therefore, dilution is not necessary. Sources of BOD include leaves and woody debris; dead plants and animals; animal manure; effluents from pulp and paper mills, wastewater treatment plants, feedlots, and foodprocessing plants; failing septic systems; and urban stormwater runoff. Note: To evaluate the potential of raw water for use as a drinking water supply, the water is usually sampled, analyzed, and tested for biochemical oxygen demand when turbid, polluted water is the only source available.

Sampling Considerations Biochemical oxygen demand is affected by the same factors that affect dissolved oxygen (see above). Aeration of stream water—by rapids and waterfalls, for example—will accelerate the decomposition of organic and inorganic material. BOD levels at a sampling site with slower, deeper waters might be higher for a given column of organic and inorganic material than the levels for a similar site in high aerated waters. Chlorine can also affect BOD measurement by inhibiting or killing the microorganisms that decompose the organic and inorganic matter in a sample. When sampling in chlorinated waters (such as those below the effluent from a sewage treatment plant), it is necessary to neutralize the chlorine

with sodium thiosulfate (see Standard Methods). Biochemical oxygen demand measurement requires taking two samples at each site. One is tested immediately for dissolved oxygen, and the second is incubated in the dark at 20°C for 5 days and then tested for the dissolved oxygen remaining. The difference in oxygen levels between the first test and the second test (in milligrams per liter) is the amount of BOD. This represents the amount of oxygen consumed by microorganisms and used to break down the organic matter present in the sample bottle during the incubation period. Because of the 5-day incubation, the tests are conducted in a laboratory. Sometimes by the end of the 5-day incubation period, the dissolved oxygen level is zero. This is especially true for rivers and streams with a lot of organic pollution. Because it is not possible to know when the zero point was reached, determining the BOD level is also impossible. In this case, diluting the original sample by a factor that results in a final dissolved oxygen level of at least 2 mg/L is necessary. Special dilution water should be used for the dilutions. Some experimentation is necessary to determine the appropriate dilution factor for a particular sampling site. The final result is the difference in dissolved oxygen between the first measurement and the second, after multiplying the second result by the dilution factor. Standard Methods prescribes all phases of procedures and calculations for BOD determination. A BOD test is not required for monitoring water supplies.

TEMPERATURE An ideal water supply should have, at all times, an almost constant temperature or one with minimum variation. Knowing the temperature of the water supply is important because the rates of biological and chemical processes depend on it. Temperature affects the oxygen content of the water (oxygen levels become lower as temperature increases), the rate of photosynthesis by aquatic plants, the metabolic rates of aquatic organisms, and the sensitivity of organisms to toxic wastes, parasites, and diseases. Causes of temperature change include weather, removal of shading stream-bank vegetation, impoundments (a body of water confined by a barrier, such as a dam), discharge of cooling water, urban stormwater, and groundwater inflows to the stream.

sampling and Equipment considerations Temperature in a stream varies with width and depth, and the temperature of well-sunlit portions of a stream can be significantly higher than the shaded portion of the water on a sunny day. In a small stream, the temperature will be relatively constant as long as the stream is uniformly in sun or shade. In a large stream, temperature can vary considerably with width and depth, regardless of shade. If safe to do so, temperature measurements should be collected at varying depths and across the surface of the stream to obtain vertical and horizontal temperature profiles. This can be done at each site at least once to determine the necessity of collecting a profile during each sampling visit. Temperature should be measured at the same place every time. Temperature is measured in the stream with a thermometer or a meter. Alcohol-filled thermometers are preferred over mercury-filled ones because they are less hazardous if broken. Armored thermometers for field use can withstand more abuse than unprotected glass thermometers and are worth the additional expense. Meters for other tests, such as pH (acidity) or dissolved oxygen, also measure temperature and can be used instead of a thermometer.

HARDNESS Water hardness refers primarily to the amount of dissolved calcium and magnesium in the water and their effects on scaling, corrosion, and soap. With hard water, it is difficult to produce a soap lather. Hard waters leave spots on glasses, a film on laundry and hair, and crusty deposits on bathroom fixtures. The presence of hardness in water supplies contributes to taste, odor, color, or turbidity, but water hardness has no health significance (Hauser, 2002). Calcium and magnesium enter water mainly by leaching of rocks. Calcium is the most abundant dissolved cationic constituent of natural freshwaters. Cal-

cium is an important component of aquatic plant cell walls and the shells and bones of many aquatic organisms. Magnesium is an essential nutrient for plants and is a component of the chlorophyll molecule. Hardness test kits express test results in ppm of CaCO_3 , but these results can be converted directly to calcium or magnesium concentrations:

Calcium hardness as ppm $\text{CaCO}_3 \times 0.40 = \text{ppm Ca}$ (10.1) Magnesium hardness as ppm $\text{CaCO}_3 \times 0.24 = \text{ppm Mg}$ (10.2) Note: Because of less contact with soil minerals and more contact with rain, surface raw water is usually softer than groundwater. As a general rule of thumb, when hardness is greater than 150 mg/L, softening treatment may be required for public water systems. Hardness determination via testing is required to monitor the efficiency of treatment. measuring hardness A hardness test follows a procedure similar to an alkalinity test, but the reactions involved are different. After the sample is carefully measured, a buffer is added to the sample to correct pH for the test and an indicator to signal the titration endpoint.

The indicator reagent is normally blue in a sample of pure water, but if calcium or magnesium ions are present in the sample the indicator combines with them to form a red complex. The titrant in this test is ethylenediaminetetraacetic acid (EDTA), used with its salts in the titration method; EDTA serves as a chelant that pulls the calcium and magnesium ions away from the red complex. The EDTA is added dropwise to the sample until all the calcium and magnesium ions have been chelated away from the complex and the indicator returns to its normal blue color. The amount of EDTA required to cause the color change is a direct indication of the amount of calcium and magnesium ions in the sample. Some hardness kits include an additional indicator that is specific for calcium. This type of kit will provide three readings: total hardness, calcium hardness, and magnesium hardness. For more information on interference, precision, and accuracy, consult the latest edition of Standard Methods.

pH It was pointed out earlier that pH is a term used to indicate the alkalinity or acidity of a substance as ranked on a scale from 1.0 to 14.0. Acidity increases as the pH gets lower. Figure 10.3 presents the pH of some common liquids.

analytical and equipment considerations The pH of water can be analyzed in the field or in the lab. If analyzed in the lab, it must be measured within 2 hours of the sample collection, because the pH will change due to the carbon dioxide from the air dissolving in the water, bringing the pH toward 7. If a high degree of accuracy and precision in pH results is required, the pH should be measured with a laboratory-quality pH meter and electrode. Meters of this quality range in cost from around \$250 to \$1000. Color comparators and pH “pocket pals” are suitable for most other purposes. The cost of either of these is in the \$50 range. The lower cost of the alternatives might be attractive if multiple samplers are used to sample several sites at the same time.

pH meters A pH meter measures the electric potential (millivolts) across an electrode when immersed in water. This electric potential is a function of the hydrogen ion activity in the sample; therefore, pH meters can display results in either millivolts (mV) or pH units. A pH meter consists of a potentiometer, which measures electric potential where it meets the water sample; a reference electrode, which provides a constant electric potential; and a temperature compensating device, which adjusts the readings according to the temperature of the sample (because pH varies with temperature). The reference and glass electrodes are frequently combined into a single probe called a combination electrode. A wide variety of meters is available, but the most important part of the pH meter is the electrode; thus, purchasing a good, reli-

able electrode and following the manufacturer's instructions for proper maintenance are important. Infrequently used or improperly maintained electrodes are subject to corrosion, which makes them highly inaccurate.

pH “pocket pals” and **color comparators** pH “pocket pals” are electronic handheld “pens” that are dipped in the water to obtain a digital readout of the pH. They can be calibrated to only one pH buffer. (Lab meters, on the other hand, can be calibrated to two or more buffer solutions and thus are more accurate over a wide range of pH measurements.) Color comparators involve adding a reagent to the sample that colors the sample water. The intensity of the color is proportional to the pH of the sample and is matched against a standard color chart. The color chart equates particular colors to associated pH values, which can be determined by matching the colors from the chart to the color of the sample. For instructions on how to collect and analyze samples, consult the latest edition of *Standard Methods*.

TURBIDITY Turbidity is a measure of water clarity—how much the material suspended in water decreases the passage of light through the water. Suspended materials include soil particles (clay, silt, and sand), algae, plankton, and microbes, among other substances. These materials are typically in the size range of 0.004 mm (clay) to 1.0 mm (sand). Turbidity can affect the color of the water, and higher turbidity increases water temperature because suspended particles absorb more heat. This in turn reduces the concentration of DO because warm water holds less DO than cold. Higher turbidity also reduces the amount of light penetrating the water, which reduces photosynthesis and the production of DO. Suspended materials can clog fish gills, reducing resistance to disease in fish, lowering growth rates, and affecting egg and larval development. As the particles settle, they can blanket the stream bottom (especially in slower waters) and smother fish eggs and benthic macroinvertebrates. Sources of turbidity include

- Soil erosion
- Waste discharge
- Urban runoff
- Eroding stream banks
- Large numbers of bottom feeders (such as carp), which can stir up bottom sediments
- Excessive algal growth

sampling and Equipment considerations Turbidity can be useful as an indicator of the effects of runoff from construction, agricultural practices, logging activity, discharges, and other sources. Turbidity often increases sharply during rainfall, especially in developed watersheds, which typically have relatively high proportions of impervious surfaces. The flow of stormwater runoff from impervious surfaces rapidly increases stream velocity, which increases the erosion rates of streambanks and channels. Turbidity can also rise sharply during dry weather if earth-disturbing activities occur in or near a stream without erosion control practices in place. Regular monitoring of turbidity can help detect trends that might indicate increasing erosion in developing watersheds; however, turbidity is closely related to stream flow and velocity and should be correlated with these factors. Comparisons of the change in turbidity over time, therefore, should be made at the same point at the same flow. Turbidity is not a measure of the amount of suspended solids present or the rate of sedimentation of a stream, as it represents only the amount of light that is scattered by suspended particles. Measurement of total solids is a more direct measurement of the amount of material suspended and dissolved in water. Turbidity is generally measured by using a turbidity meter. Volunteer programs may also take samples to a lab for analysis. Another approach is to measure transparency (an integrated measure of light scattering and absorption) instead of turbidity. Water clarity or transparency can be measured using a Secchi disk (see Figure 10.4) or transparency tube. The Secchi disk can only be used in deep, slow-moving rivers; the transparency tube (a comparatively new development) is gaining acceptance around the country but is not yet in wide use. A turbidity meter consists of

a light source that illuminates a water sample and a photoelectric cell that measures the intensity of light scattered at a 90° angle by the particles in the sample. It measures turbidity in nephelometric turbidity units (NTUs). Meters can measure turbidity over a wide range—from 0 to 1000 NTUs. A clear mountain stream might have a turbidity of around 1 NTU, whereas a large river such as the Mississippi might have a dry-weather turbidity of 10 NTUs. Because these values can jump into hundreds of NTUs during runoff events, the turbidity meter to be used should be reliable over the range in which you will be working. Meters of this quality cost about \$800. Many meters in this price range are designed for field or lab use. Although turbidity meters can be used in the field, samplers might want to collect samples and take them to a central point for turbidity measurements because of the expense of the meter. Most programs can afford only one and would have to pass it along from site to site, complicating logistics and increasing the risk of damage to the meter. Meters also include glass cells that must remain optically clear and free of scratches for operation. Samplers can also take turbidity samples to a lab for meter analysis at a reasonable cost.

Using a Secchi Disk A Secchi disk is a black and white disk that is lowered by hand into the water to the depth at which it vanishes from sight (see Figure 10.4). The distance to vanishing is then recorded—the clearer the water, the greater the distance. Secchi disks are simple to use and inexpensive. For river monitoring they have limited use, because in most cases the river bottom will be visible and the disk will not reach a vanishing point. Deeper, slower moving rivers are the most appropriate places for Secchi disk measurement, although the current might require that the disk be weighted so it does not sway and make measurement difficult. Secchi disks cost about \$50 but can be homemade. The line attached to the Secchi disk must be marked in waterproof ink according to units designated by the sampling program. Many programs require samplers to measure to the nearest 1/10 meter. Meter intervals can be tagged (e.g., with duct tape) for ease of use. To measure water clarity with a Secchi disk:

1. Check to make sure that the Secchi disk is securely attached to the measured line.
2. Lean over the side of the boat and lower the Secchi disk into the water, keeping your back to the sun to block glare.
3. Lower the disk until it disappears from view. Lower it one-third of a meter and then slowly raise the disk until it just reappears. Move the disk up and down until you find the exact vanishing point.
4. Attach a clothespin to the line at the point where the line enters the water. Record the measurement on your data sheet. Repeating the measurement provides you with a quality control check.

The key to consistent results is to train samplers to follow standard sampling procedures and, if possible, have the same individual take the reading at the same site throughout the season.

Transparency Tube Pioneered by Australia's Department of Conservation, the transparency tube is a clear, narrow plastic tube marked in units with a dark pattern painted on the bottom. Water is poured into the tube until the pattern disappears. Some U.S. volunteer monitoring programs, such as the Tennessee Valley Authority (TVA) Clean Water Initiative and the Minnesota Pollution Control Agency (MPCA), are testing the transparency tube in streams and rivers. The MPCA uses tubes marked in centimeters and has found tube readings to relate fairly well to lab measurements of turbidity and total suspended solids,

although they do not recommend the transparency tube for applications where precise and accurate measurement is required or in highly colored waters. The TVA and MPCA have suggested the following sampling considerations:

1. Collect the sample in a bottle or bucket in midstream and at mid-depth if possible. Avoid stagnant water, and sample as far from the shoreline as is safe. Avoid collecting sediment from the bottom of the stream.
2. Face upstream as you fill the bottle or bucket.
3. Take readings in open but shaded conditions. Turn your back to the sun to avoid direct sunlight.
4. Carefully stir or swish the water in the bucket or bottle until it is homogeneous, taking care not to produce air bubbles (these scatter light and affect the measurement). Pour the water slowly in the tube while looking down the tube. Measure the depth of the water column in the tube at the point where the symbol just disappears.

ORTHOPHOSPHATES As discussed earlier, both phosphorus and nitrogen are essential nutrients for the plants and animals that make up the aquatic food web. Because phosphorus is the nutrient in short supply in most freshwater systems, even a modest increase in phosphorus can (under the right conditions) set off a whole chain of undesirable events in a stream, including accelerated plant growth, algae blooms, low dissolved oxygen, and the death of certain fish, invertebrates, and other aquatic animals. Phosphorus comes from many sources, both natural and human. These include soil and rocks, wastewater treatment plants, runoff from fertilized lawns and cropland, failing septic systems, runoff from animal manure storage areas, disturbed land areas, drained wetlands, water treatment, and commercial cleaning preparations. Phosphorus has a complicated story. Pure, elemental phosphorus (P) is rare. In nature, phosphorus usually exists as part of a phosphate molecule (PO_4). Phosphorus in aquatic systems occurs as organic phosphate and inorganic phosphate. Organic phosphate consists of a phosphate molecule associated with a carbon-based molecule, as in plant or animal tissue. Phosphate that is not associated with organic material is inorganic, the form required by plants. Animals can use either organic or inorganic phosphate. Both organic and inorganic phosphorus can be dissolved in the water or suspended (attached to particles in the water column).

phosphorus cycle Phosphorus cycles through the environment, changing form as it does so. Aquatic plants take in dissolved inorganic phosphorus as it becomes part of their tissues. Animals get the organic phosphorus they need by eating aquatic plants, other animals, or decomposing plant and animal material. In water bodies, as plants and animals excrete wastes or die, the organic phosphorus they contain sinks to the bottom, where bacterial decomposition converts it back to inorganic phosphorus, both dissolved and attached to particles. This inorganic phosphorus gets back into the water column when the bottom is stirred up by animals, human activity, chemical interactions, or water currents. Then it is taken up by plants and the cycle begins again. In a stream system, the phosphorus cycle tends to move phosphorus downstream as the current carries decomposing plant and animal tissue and dissolved phosphorus. It becomes stationary only when it is taken up by plants or is bound to particles that settle to the bottom of ponds. In the field of water quality chemistry, phosphorus is described by several terms. Some of these

terms are chemistry based (referring to chemically based compounds), and others are methods based (they describe what is measured by a particular method). The term orthophosphate is a chemistry-based term that refers to the phosphate molecule all by itself. Reactive phosphorus is a corresponding method-based term that describes what is actually being measured when the test for orthophosphate is being performed. Because the lab procedure is not quite perfect, mostly orthophosphate is obtained along with a small fraction of some other forms. More complex inorganic phosphate compounds are referred to as condensed phosphates or polyphosphates. The method-based term for these forms is acid hydrolyzable phosphorus.

Monitoring phosphorus Monitoring phosphorus is challenging because it involves measuring very low concentrations—down to 0.01 mg/L or even lower. Even such very low concentrations of phosphorus can have a dramatic impact on streams. Less sensitive methods should be used only to identify serious problem areas. Although many tests for phosphorus exist, only four are likely to be performed by most monitors:

1. The total orthophosphate test is largely a measure of orthophosphate. Because the sample is not filtered, the procedure measures both dissolved and suspended orthophosphate. The USEPA-approved method for measuring total orthophosphate is known as the ascorbic acid method. Briefly, a reagent (either liquid or powder) containing ascorbic acid and ammonium molybdate reacts with orthophosphate in the sample to form a blue compound. The intensity of the blue color is directly proportional to the amount of orthophosphate in the water.
2. The total phosphorus test measures all the forms of phosphorus in the sample (orthophosphate, condensed phosphate, and organic phosphate) by first “digesting” (heating and acidifying) the sample to convert all the other forms to orthophosphate. The orthophosphate is then measured by the ascorbic acid method. Because the sample is not filtered, the procedure measures both dissolved and suspended orthophosphate.
3. The dissolved phosphorus test measures that fraction of the total phosphorus that is in solution in the water (as opposed to being attached to suspended particles). It is determined by first filtering the sample, then analyzing the filtered sample for total phosphorus.
4. Insoluble phosphorus is calculated by subtracting the dissolved phosphorus result from the total phosphorus result.

All of these tests have one thing in common—they all depend on measuring orthophosphate. The total orthophosphate test measures the orthophosphate that is already present in the sample. The others measure that which is already present and that which is formed when the other forms of phosphorus are converted to orthophosphate by digestion.

sampling and Equipment Considerations Monitoring phosphorus involves two basic steps:

1. Collect a water sample.
2. Analyze the sample in the field or lab for one of the types of phosphorus described above.

Refer to Standard Methods for the specific laboratory methods.

Sample Containers Sample containers made of either some form of plastic or Pyrex® glass are acceptable to the USEPA. Because phosphorus molecules have a tendency to adsorb (attach) to the inside surface of sample containers, containers that are to be reused must be acidwashed to remove adsorbed phosphorus. The container must be able to withstand repeated contact with hydrochloric acid. Plastic containers, either high-density polyethylene or polypropylene, might be preferable to glass from a practical standpoint, because they are better able to withstand breakage. Some programs use disposable, sterile, plastic Whirl-Pak® bags. The size of the container depends on the sample amount needed for the phosphorus analysis method chosen and the amount needed for other analyses to be performed.

Dedicated Labware All containers that will hold water samples or come into contact with reagents used in this test must be dedicated. They should not be used for other tests, to eliminate the possibility that reagents containing phosphorus will contaminate the labware. All labware should be acid-washed. The only form of phosphorus this text recommends for field analysis is total orthophosphate, which requires use of the ascorbic acid method on an untreated sample. Analysis of any of the other forms requires adding potentially hazardous reagents, heating the sample to boiling, and using too much time and too much equipment to be practical. In addition, analysis for other forms of phosphorus is prone to errors and inaccuracies in field situations. Pretreatment and analysis for these other forms should be handled in a laboratory.

Ascorbic Acid Method In the ascorbic acid method, a combined liquid or prepackaged powder reagent consisting of sulfuric acid, potassium antimonyl tartrate, ammonium molybdate, and ascorbic acid (or comparable compounds) is added to either 50 or 25 mL of the water sample. This colors the sample blue in direct proportion to the amount of orthophosphate in the sample. Absorbance or transmittance is then measured after 10 minutes, but before 30 minutes, using a color comparator with a scale in milligrams per liter that increases with the increase in color hue, or an electronic meter that measures the amount of light absorbed or transmitted at a wavelength of 700 to 880 nm (again, depending on manufacturer's directions). A color comparator may be useful for identifying heavily polluted sites with high concentrations (greater than 0.1 mg/L); however, matching the color of a treated sample to a comparator can be very subjective, especially at low concentrations, and can lead to variable results. A field spectrophotometer or colorimeter with a 2.5-cm light path and an infrared photocell (set for a wavelength of 700 to 880 nm) is recommended for accurate determination of low concentrations (between 0.2 and 0.02 mg/L). Use of a meter requires that a prepared known standard concentration be analyzed ahead of time to convert the absorbance readings of a stream sample to milligrams per liter or that the meter reads directly in milligrams per liter. For information on how to prepare standard concentrations and on how to collect and analyze samples, consult the latest edition of *Standard Methods* or Method 365.2 of *Methods for Chemical Analysis of Water and Wastes* (USEPA, 1983).

NITRATES Nitrates are a form of nitrogen found in several different forms in terrestrial and aquatic ecosystems. These forms of nitrogen include ammonia (NH_3), nitrates (NO_3), and nitrites (NO_2). Nitrates are essential plant nutrients, but excess amounts can cause significant water quality problems. Together with phosphorus, nitrates in excess amounts can accelerate eutrophication, causing dramatic increases in aquatic plant growth and changes in the types of plants and animals that live in the stream. This, in turn, affects dissolved oxygen, temperature, and other indicators. Excess nitrates can cause hypoxia (low levels of dissolved oxygen) and can become toxic to warm-blooded animals at higher concentrations (10 mg/L or higher) under certain conditions. The natural level of ammonia or nitrate in surface water is typically low (less than 1 mg/L), but in the effluent of wastewater treatment plants it can range up to 30 mg/L. Sources of nitrates include wastewater treatment plants, runoff from fertilized lawns and cropland, failing on-site septic systems, runoff from animal manure storage areas, and industrial discharges that contain corrosion inhibitors.

sampling and eEquipment consiDerations Nitrates from land sources end up in rivers and streams more quickly than other nutrients such as phosphorus because they dissolve in water more readily than phosphorus, which has an attraction for soil particles. As a result, nitrates serve as a better indicator of the

possibility of a source of sewage or manure pollution during dry weather. Water that is polluted with nitrogen-rich organic matter might show low nitrates. Decomposition of the organic matter lowers the dissolved oxygen level, which in turn slows the rate at which ammonia is oxidized to nitrite (NO_2) and then to nitrate (NO_3). Under such circumstances, monitoring for nitrites or ammonia (considerably more toxic to aquatic life than nitrate) might also be necessary. (See Standard Methods, Section 4500-NH₃ and Section 4500-NH₂, for appropriate nitrite methods). Water samples to be tested for nitrate should be collected in glass or polyethylene containers that have been prepared by using Method B (presented earlier). Most monitoring programs usually use two methods for nitrate testing: the cadmium reduction method and the nitrate electrode method. The more commonly used cadmium reduction method produces a color reaction measured either by comparison to a color wheel or by use of a spectrophotometer. A few programs also use a nitrate electrode, which can measure in the range of 0 to 100 mg/L nitrate. A newer colorimetric immunoassay technique for nitrate screening is also now available.

Cadmium Reduction Method The cadmium reduction method is a colorimetric method that involves contact of the nitrate in the sample with cadmium particles, which cause nitrates to be converted to nitrites. The nitrites then react with another reagent to form a red color, in proportional intensity to the original amount of nitrate. The color is measured either by comparison to a color wheel with a scale in milligrams per liter that increases with the increase in color hue or by use of an electronic spectrophotometer that measures the amount of light absorbed by the treated sample at a 543-nm wavelength. The absorbance value converts to the equivalent concentration of nitrate against a standard curve. Methods for making standard solutions and standard curves are presented in Standard Methods. Before each sampling run, the sampling/monitoring supervisor should create this curve. The curve is developed by making a set of standard concentrations of nitrate, reacting them, and developing the corresponding color, then plotting the absorbance value for each concentration against concentration. A standard curve could also be generated for the color wheel. Use of the color wheel is appropriate only if nitrate concentrations are greater than 1 mg/L. For concentrations below 1 mg/L, use a spectrophotometer. Matching the color of a treated sample at low concentrations to a color wheel (or cubes) can be very subjective and can lead to variable results. Color comparators can, however, be effectively used to identify sites with high nitrates. This method requires that the samples being treated are clear. If a sample is turbid, filter it through a 0.45- μm filter. Be sure to test to make sure the filter is nitrate free. If copper, iron, or other metals are present in concentrations above several milligrams per liter, the reaction with the cadmium will slow down and the reaction time must be increased. The reagents used for this method are often prepackaged for different ranges, depending on the expected concentration of nitrate in the stream. For example, the Hach Company provides reagents for the following ranges: low (0 to 0.40 mg/L), medium (0 to 4.5 mg/L), and high (0 to 30 mg/L). Determining the appropriate range for the stream being monitored is important.

Nitrate Electrode Method A nitrate electrode (used with a meter) is similar in function to a dissolved oxygen meter. It consists of a probe with a sensor that measures nitrate activity in the water; this activity affects the electric potential of a solution in the probe. This change is then transmitted to the meter, which converts the electric signal to a scale that is read in millivolts, and the millivolts are converted to milligrams per liter of nitrate by plotting them against a standard curve. The accuracy of the electrode can be affected by high concentrations of chloride or bicarbonate ions in the sample water. Fluctuating pH levels can also affect the meter reading. Nitrate electrodes and meters are expensive compared to field kits

that employ the cadmium reduction method. (The expense is comparable, however, if a spectrophotometer is used rather than a color wheel.) Meter and probe combinations run between \$700 and \$1200, including a long cable to connect the probe to the meter. If the program has a pH meter that displays readings in millivolts, it can be used with a nitrate probe and no separate nitrate meter is needed. Results are read directly as milligrams per liter. Although nitrate electrodes and spectrophotometers can be used in the field, they have certain disadvantages. These devices are more fragile than the color comparators and are therefore more at risk of breaking in the field. They must be carefully maintained and must be calibrated before each sample run or, if many tests are being run, between samplings. This means that samples are best tested in the lab. Note that samples to be tested with a nitrate electrode should be at room temperature, whereas color comparators can be used in the field with samples at any temperature.

TOTAL SOLIDS Total solids are dissolved solids plus suspended and settleable solids in water. In stream water, dissolved solids consist of calcium, chlorides, nitrate, phosphorus, iron, sulfur, and other ions—particles that will pass through a filter with pores of around 2 μm (0.002 cm) in size. Suspended solids include silt and clay particles, plankton, algae, fine organic debris, and other particulate matter. These are particles that will not pass through a 2- μm filter. The concentration of total dissolved solids affects the water balance in the cells of aquatic organisms. An organism placed in water with a very low level of solids (distilled water, for example) swells because water tends to move into its cells, which have a higher concentration of solids. An organism placed in water with a high concentration of solids shrinks somewhat, because the water in its cells tends to move out. This in turn affects the ability of the organism to maintain the proper cell density, which makes keeping its position in the water column difficult. It might float up or sink down to a depth to which it is not adapted, and it might not survive. Higher concentrations of suspended solids can serve as carriers of toxics, which readily cling to suspended particles. This is particularly a concern where pesticides are being used on irrigated crops. Where solids are high, pesticide concentrations may increase well beyond those of the original application as the irrigation water travels down irrigation ditches. Higher levels of solids can also clog irrigation devices and might become so high that irrigated plant roots will lose water rather than gain it. A high concentration of total solids will make drinking water unpalatable and might have an adverse effect on people who are not used to drinking such water. Levels of total solids that are too high or too low can also reduce the efficiency of wastewater treatment plants, as well as the operation of industrial processes that use raw water. Total solids affect water clarity. Higher solids decrease the passage of light through water, thereby slowing photosynthesis by aquatic plants. Water heats up more rapidly and holds more heat; this, in turn, might adversely affect aquatic life adapted to a lower temperature regime. Sources of total solids include industrial discharges, sewage, fertilizers, road runoff, and soil erosion. Total solids are measured in milligrams per liter (mg/L).

sampling and Equipment considerations Total solids are important to measure in areas where discharges from sewage treatment plants, industrial plants, or extensive crop irrigation may occur. In particular, streams and rivers in arid regions where water is scarce and evaporation is high tend to have higher concentrations of solids and are more readily affected by the human introduction of solids from land use activities. Total solids measurements can be useful as an indicator of the effects of runoff from construction, agricultural practices, logging activities, sewage treatment plant discharges, and other sources. As with turbidity, concentrations often increase sharply during rainfall, especially in developed watersheds. They can also rise sharply during dry weather if earth-disturbing activities occur in or near the stream

without erosion control practices in place. Regular monitoring of total solids can help detect trends that might indicate increasing erosion in developing watersheds. Total solids are closely related to stream flow and velocity and should be correlated with these factors. Any change in total solids over time should be measured at the same site at the same flow. Total solids are measured by weighing the amount of solids present in a known volume of sample. This is accomplished by weighing a beaker, filling it with a known volume, evaporating the water in an oven, and completely drying the residue, then weighing the beaker with the residue. The total solids concentration is equal to the difference between the weight of the beaker with the residue and the weight of the beaker without it. Because the residue is so light in weight, the lab must have a balance that is sensitive to weights in the range of 0.0001 g. Balances of this type are called analytical or Mettler balances, and they are expensive (around \$3000). The technique requires that the beakers be kept in a desiccator—a sealed glass container that contains material that absorbs moisture and ensures that the weighing is not biased by water condensing on the beaker. Some desiccants change color to indicate moisture content. The measurement of total solids cannot be done in the field. Samples must be collected using clean glass or plastic bottles or Whirl-Pak® bags and taken to a laboratory where the test can be run.

CONDUCTIVITY Conductivity is a measure of the ability of water to pass an electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge). Organic compounds such as oil, phenol, alcohol, and sugar do not conduct electrical current very well and therefore have a low conductivity when in water. Conductivity is also affected by temperature—the warmer the water, the higher the conductivity. Conductivity in streams and rivers is affected primarily by the geology of the area through which the water flows. Streams that run through areas with granite bedrock tend to have lower conductivity because granite is composed of more inert materials that do not ionize (dissolve into ionic components) when washed into the water. On the other hand, streams that run through areas with clay soils tend to have higher conductivity, because of the presence of materials that ionize when washed into the water. Groundwater inflows can have the same effects, depending on the bedrock they flow through. Discharges to streams can change the conductivity depending on their make-up. A failing sewage system would raise the conductivity because of the presence of chloride, phosphate, and nitrate; an oil spill would lower conductivity. The basic unit of measurement of conductivity is the mho or siemens. Conductivity is measured in micromhos per centimeter ($\mu\text{mho}/\text{cm}$) or microsiemens per centimeter ($\mu\text{S}/\text{cm}$). Distilled water has a conductivity in the range of 0.5 to 3 $\mu\text{mho}/\text{cm}$. The conductivity of rivers in the United States generally ranges from 50 to 1500 $\mu\text{mho}/\text{cm}$. Studies of inland freshwaters indicate that streams supporting good mixed fisheries have a range between 150 and 500 $\mu\text{mho}/\text{cm}$. Conductivity outside this range could indicate that the water is not suitable for certain species of fish or macroinvertebrates. Industrial waters can range as high as 10,000 $\mu\text{mho}/\text{cm}$.

sampling and eQuipment consiDerations Conductivity is useful as a general measure of stream water quality. Each stream tends to have a relatively constant range of conductivity that, once established, can be used as a baseline for comparison with regular conductivity measurements. Significant changes in conductivity could indicate that a discharge or some other source of pollution has entered a stream. Conductivity is measured with a probe and a meter. Voltage is

applied between two electrodes in a probe immersed in the sample water. The drop in voltage caused by the resistance of the water is used to calculate the conductivity per centimeter. The meter converts the probe measurement to micromhos per centimeter ($\mu\text{mho}/\text{cm}$) and displays the result for the user. Note: Some conductivity meters can also be used to test for total dissolved solids and salinity. The total dissolved solids concentration in milligrams per liter (mg/L) can also be calculated by multiplying the conductivity result by a factor between 0.55 and 0.9, which is empirically determined (see Method 2510 in Standard Methods). Suitable conductivity meters cost about \$350. Meters in this price range should also measure temperature and automatically compensate for temperature in the conductivity reading. Conductivity can be measured in the field or the lab. In most cases, collecting samples in the field and taking them to a lab for testing is probably better. In this way, several teams can collect samples simultaneously. If testing in the field is important, meters designed for field use can be obtained for around the same cost mentioned above. If samples will be collected in the field for later measurement, the sample bottle should be a glass or polyethylene bottle that has been washed in phosphate-free detergent and rinsed thoroughly with both tap and distilled water. Factory-prepared Whirl-Pak® bags may also be used.

TOTAL ALKALINITY Alkalinity is a measure of the capacity of water to neutralize acids. Alkaline compounds in the water, such as bicarbonates (baking soda is one type), carbonates, and hydroxides, remove H^+ ions and lower the acidity of the water (increasing the pH). They usually do this by combining with the H^+ ions to make new compounds. Without this acid-neutralizing capacity, any acid added to a stream would cause an immediate change in the pH. Measuring alkalinity is important in determining the ability of a stream to neutralize acidic pollution from rainfall or wastewater—one of the best measures of the sensitivity of the stream to acid inputs. Alkalinity in streams is influenced by rocks and soils, salts, certain plant activities, and certain industrial wastewater discharges. Total alkalinity is determined by measuring the amount of acid (e.g., sulfuric acid) required to bring the sample to a pH of 4.2. At this pH, all the alkaline compounds in the sample are used up. The result is reported as milligrams per liter of calcium carbonate ($\text{mg}/\text{L CaCO}_3$).

analytical and eEquipment consiDerations For total alkalinity, a double-endpoint titration using a pH meter (or pH “pocket pal”) and a digital titrator or burette is recommended. This can be done in the field or in the lab. If alkalinity must be analyzed in the field, a digital titrator should be used instead of a burette, because burettes are fragile and more difficult to set up and use in the field. The alkalinity method described below was developed by the Acid Rain Monitoring Project of the University of Massachusetts Water Resources Research Center (River Watch Network, 1992).

Burettes, Titrators, and Digital Titrators for Measuring Alkalinity The total alkalinity analysis involves titration. In this test, titration is the addition of small, precise quantities of sulfuric acid (the reagent) to the sample until the sample reaches a certain pH (the endpoint). The amount of acid used corresponds to the total alkalinity of the sample. Alkalinity can be measured using a burette, titrator, or digital titrator (described below):

- A burette is a long, graduated glass tube with a tapered tip like a pipette and a valve that opens to allow the reagent to drip out of the tube. The amount of reagent used is calculated by subtracting the original volume in the burette from the column left after the endpoint has been reached. Alkalinity is calculated based on the amount used.
- Titrators forcefully expel the reagent by using a manual or mechanical plunger. The amount of reagent used is calculated by subtracting the original volume in the titra-

tor from the volume left after the endpoint has been reached. Alkalinity is then calculated based on the amount used or is read directly from the titrator. • Digital titrators have counters that display numbers. A plunger is forced into a cartridge containing the reagent by turning a knob on the titrator. As the knob turns, the counter changes in proportion to the amount of reagent used. Alkalinity is then calculated based on the amount used. Digital titrators cost about \$100 or more. Digital titrators and burettes allow for much more precision and uniformity in the amount of titrant that is used.

FECAL BACTERIA* Members of two bacteria groups (coliforms and fecal streptococci) are used as indicators of possible sewage contamination, because they are commonly found in human and animal feces. Although they are generally not harmful themselves, they indicate the possible presence of pathogenic (disease-causing) bacteria, viruses, and protozoa that also live in human and animal digestive systems. Their presence in streams suggests that pathogenic microorganisms might also be present and that swimming in that water or eating shellfish from that water might present a health risk. Because testing directly for the presence of a large variety of pathogens is difficult, time consuming, and expensive, water is usually tested for coliforms and fecal streptococci instead. Sources of fecal contamination of surface waters include wastewater treatment plants, on-site septic systems, domestic and wild animal manure, and storm runoff. In addition to the possible health risk associated with the presence of elevated levels of fecal bacteria, the bacteria can also cause cloudy water, unpleasant odors, and an increased oxygen demand.

- Much of the information presented in the following sections is adapted from USEPA, Test Methods for *Escherichia coli* and Enterococci in Water by the Membrane Filter Procedure, EPA 600/4-85-076, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH, 1985; USEPA, Bacteriological Ambient Water Quality Criteria for Marine and Fresh Recreational Waters, EPA 440/5-84-002, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH, 1986.

Indicator bacteria types The most commonly tested fecal bacteria indicators are total coliforms, fecal coliforms, *Escherichia coli*, fecal streptococci, and enterococci. All but *E. coli* are composed of a number of species of bacteria that share common characteristics, including shape, habitat, or behavior; *E. coli* is a single species in the fecal coliform group. Total coliforms are widespread in nature. All members of the total coliform group can occur in human feces, but some can also be present in animal manure, soil, and submerged wood and in other places outside the human body. The usefulness of total coliforms as an indicator of fecal contamination depends on the extent to which the bacteria species found are fecal and human in origin. For recreational waters, total coliforms are no longer recommended as an indicator. For drinking water, total coliforms are still the standard test, because their presence indicates contamination of a water supply by an outside source. Fecal coliforms, a subset of total coliform bacteria, are more fecal specific in origin; however, even this group contains a genus, *Klebsiella*, with species that are not necessarily fecal in origin. *Klebsiella* are commonly associated with textile and pulp and paper mill wastes. If these sources discharge to a local stream, consideration should be given to monitoring more fecal and human-specific bacteria. For recreational waters, this group was the primary bacteria indicator until relatively recently, when the USEPA began recommending *E. coli* and enterococci as better indicators of health risk from water contact. Fecal coliforms are still being used in many states as indicator bacteria. *E. coli* is a species of fecal coliform bacteria specific to fecal material from humans and other warm-blooded

animals. The USEPA recommends *E. coli* as the best indicator of health risk from water contact in recreational waters; some states have changed their water quality standards and are monitoring accordingly. Fecal streptococci generally occur in the digestive systems of humans and other warm-blooded animals. In the past, fecal streptococci were monitored together with fecal coliforms, and a ratio of fecal coliforms to streptococci was calculated. This ratio was used to determine whether the concentration was of human or nonhuman origin; however, this is no longer recommended as a reliable test. *Enterococcus* spp. are a subgroup within the fecal *Streptococcus* group. Enterococci are distinguished by their ability to survive in saltwater, and in this respect they more closely mimic many pathogens than do the other indicators. Enterococci are typically more human specific than the larger fecal *Streptococcus* group. The USEPA recommends enterococci as the best indicator of health risk in saltwater used for recreation and as a useful indicator in freshwater, as well.

Which bacteria should be monitored? Which bacteria chosen for testing depends on what is to be determined. Does swimming in the local stream pose a health risk? Does the local stream meet state water quality standards? Studies conducted by the USEPA to determine the correlation between different bacterial indicators and the occurrence of digestive system illness at swimming beaches suggest that the best indicators of health risk from recreational

water contact in freshwater are *Escherichia coli* and *Enterococcus* spp. For saltwater, enterococci are the best. Interestingly, fecal coliforms as a group were determined to be a poor indicator of the risk of digestive system illness; however, many states continue to use fecal coliforms as their primary health risk indicator. If your state is still using the total of fecal coliforms measurement as the indicator bacteria and you want to know whether the water meets state water quality standards, you should monitor fecal coliforms. If, however, you want to determine the health risk from recreational water contact, the results of the USEPA studies suggest that you should consider switching to the *E. coli* or enterococci method for testing freshwater. In any case, consulting with the water quality division of your state's environmental agency is best, especially if you expect them to use your data.

Sampling and Equipment Considerations Bacteria can be difficult to sample and analyze, for many reasons. Natural bacteria levels in streams can vary significantly; bacteria conditions are strongly correlated with rainfall; thus, comparing wet and dry weather bacteria data can be a problem. Many analytical methods have a low level of precision yet can be quite complex to accomplish; and absolutely sterile conditions are essential to maintain while collecting and handling samples. The primary equipment decision to make when sampling for bacteria is what type and size of sample container you will use. Once you have made that decision, the same straightforward collection procedure is used, regardless of the type of bacteria being monitored. When monitoring bacteria, all containers and surfaces with which the sample will come into contact must be sterile. Containers made of either some form of plastic or Pyrex® glass are acceptable to the USEPA; however, if the containers are to be reused, they must be sturdy enough to survive sterilization using heat and pressure. The containers can be sterilized by using an autoclave, a machine that sterilizes with pressurized steam. When an autoclave is used, the container material must be able to withstand high temperatures and pressure. Plastic containers—either high density polyethylene or polypropylene—might be preferable to glass from a practical standpoint because they will better withstand breakage. In any case, be sure to check the manufacturer's specifications to see whether the container can withstand 15 minutes in an autoclave at a temperature of 121°C without melting. (Extreme

caution is advised when working with an autoclave.) Disposable, sterile, plastic Whirl-Pak® bags are used by a number of programs. The size of the container depends on the sample amount needed for the bacteria analysis method you choose and the amount needed for other analyses. The two basic methods for analyzing water samples for bacteria in common use are the membrane filtration and multiple-tube fermentation methods. Given the complexity of the analysis procedures and the equipment required, field analysis of bacteria is not recommended. Bacteria can either be analyzed at a well-equipped lab or sent to a state-certified lab for analysis. If a bacteria sample is sent to a private lab, make sure that the lab is certified by the state for bacteria analysis. Consider state water quality labs, university and college labs, private labs, wastewater treatment plant labs, and hospitals. This text does not address laboratory methods, because

several bacteria types are commonly monitored and the methods are different for each type. For more information on laboratory methods, consult the latest edition of Standard Methods. Note: If you decide to analyze your samples in your own lab, be sure to carry out a quality assurance/quality control program.

APPARENT COLOR Some aspects of water quality can be judged by its color. Noticeable color is an objectionable characteristic that makes the water psychologically unacceptable to the consumer (DeZuane, 1997). Pure water is colorless, but water in nature is often colored by foreign substances. The color in water that is partly due to dissolved solids that remain after removal of suspended matter is known as true color. Apparent color (the topic of this section) results from dissolved substances and suspended matter and provides useful information about the source and content of the water. Simply stated, when turbidity is present, so is apparent color. Natural metallic ions, plankton, algae, industrial pollution, and plant pigments from humus and peat may all produce color in water. Pure water absorbs different wavelengths (colors) of light at different rates. Blue and blue-green light are the wavelengths best transmitted through water, so a white surface under “colorless” water looks blue (e.g., Caribbean and some South Pacific Island waters above white sand). Over the years, several attempts to standardize the method of describing the “apparent” color of water using comparisons to color standards have been made. Standard Methods recognizes the visual comparison method as a reliable method of analyzing water from the distribution system. One of the visual comparison methods is the Forel-Ule Color Scale, consisting of a dozen shades ranging from deep blue to khaki green, typical of offshore and coastal bay waters. By using established color standards, people in different areas can compare test results. Another visual comparison method is the Borger Color System, which provides an inexpensive, portable color reference for shades typically found in natural waters and can also be used for its original purpose—describing the colors of insects and larvae found in streams or lakes. The Borger Color System also allows the recording of the color of algae and bacteria on stream beds. Note: Do not leave color standard charts and comparators in direct sunlight. Measured levels of color in water can serve as indicators for a number of conditions; for example, transparent water with a low accumulation of dissolved minerals and particulate matter usually appears blue and indicates low productivity. Yellow to brown color normally indicates that the water contains dissolved organic materials, humic substances from soil, peat, or decaying plant material water. Deeper yellow to reddish colors in water indicate the presence of some algae and dinoflagellates in the water. Water rich in phytoplankton and other algae appears green. A variety of yellow, reds, browns, and grays is indicative of soil runoff. To ensure reliable and accurate descriptions of apparent color, use a system of color comparison that is reproducible and comparable to the systems used by other groups.

ODOR Odor in water is caused by chemicals that may come from municipal and industrial waste discharges or natural sources such as decomposing vegetable matter or microbial activity. Odor affects the acceptability of drinking water, the aesthetics of recreation water, and the taste of aquatic foodstuffs. A wide variety of smells can be accurately detected by the human nose, which is the best odor-detection and -testing device currently available. To measure odor, collect a sample in a large mouthed jar. After waving off the air above the water sample with your hand, smell the sample. Use the list of odors provided in Standard Methods (a system of qualitative description that helps monitors describe and record detected odors; see Table 10.6) to describe the smells. Record all observations.

SUMMARY All of the elements that comprise the standard practices associated with proper water monitoring provide drinking water practitioners with the technical and scientific data necessary to determine the level and types of treatment required to successfully condition water obtained from surface and ground-water sources. Drinking water treatment is covered in Chapter 11.

Water Treatment Developing world cities with private water-management companies have been plagued by lapses in service, soaring costs, corruption and worse. In Manila, where the water system is controlled by Suez, San Francisco-based Bechtel and the prominent Ayala family, water is only reliably available for a few hours a day, and rate increases have been so severe that the poorest families must choose each month between paying for water and two days' worth of food. In 2001 the government of Ghana agreed to privatize local water systems as a condition for an IMF loan. To attract investors, the government doubled water rates, setting off protests in a country where the average annual income is less than \$400 a year and the water bill (for those fortunate enough to have running water) can run upwards of \$110. In Cochabamba, the third-largest city in Bolivia, water rates shot up by 35 per cent after a consortium led by Bechtel took over the city's water system in 1999; some residents found themselves paying 20 per cent of their income on water. An initial round of peaceful street protests led to riots in which six people were killed. Eventually, the Bolivian government voided Bechtel's contract and told the company's officials it could not guarantee their safety if they stayed in town. Privatization has also spawned protests (and, in some cases, even dominated elections) in Paraguay, where police turned water cannons on anti-privatization protesters, Panama, Brazil, Peru, Colombia, India, Pakistan, Hungary and South Africa. Louma (2004)

It is common practice to treat wastewater to the point where it is cleaner than the local waterways into which it is ultimately released. Eventually, it arrives at the ocean, with absolutely no downstream use—this is referred to as one-and-done usage. Why waste such a valuable resource? Why not reuse it? But we do already reuse it to some extent . . . through de facto water recycling, as shown in Figure 11.1.

INTRODUCTION We live on a planet with a surface that is three-fourths covered with water, so we recognize the irony inherent in the fact that many areas of the world face critical shortages of drinking water. Most of Earth's water is seawater, of course—far too saline for human consumption. Of the little “fresh” water that remains, most is trapped in polar ice caps, where harnessing it for use is difficult. Much of the accessible natural supply of potable water is stressed by a growing world population, which increases the basic demand for this natural resource while reducing the supply further through contamination. Major population centers in developing nations (those without established waste treatment or water treatment infrastructure) often suffer from epidemics of waterborne disease. In these areas, raw sewage can directly contaminate the rivers and streams used for drinking, washing, and cooking. In other cases, unchecked industrialization leads to water contamination through improperly disposed of chemical and nuclear wastes.

The drinking water purveyor must ensure that the drinking water supplied is safe for human consumption. In fact, the primary reason for the development and installation of a public water system is the protection of public health. Basically, a properly operated water system serves as a line of defense between disease and the public. Properly operated water treatment and supply systems are defined as those that

- Remove or inactivate pathogenic microorganisms including bacteria, viruses, and protozoa.
- Reduce or remove chemicals that can be detrimental to health.
- Provide quality water, thus discouraging the customer from seeking better tasting or better looking water that may be contaminated.

This last point is critical, but one often overlooked in the operation and management of public water systems. When the water produced by a system is objectionable because of odor, taste, or appearance, customers will seek another source for their drinking water. Ironically, these alternative sources, although they look, taste, and smell fine (“better than city water”), could contain microorganisms or chemicals that are harmful. This chapter discusses the drinking water practitioner’s most important function: ensuring that water delivered to the public is properly treated and arrives as the clean, wholesome, safe product that it must be. Moreover, it also covers the innovative approach taken by the Hampton Roads Sanitation District (HRS D) to replacing one-and-done usage with one-and-redone usage.

CONVENTIONAL WATER TREATMENT A typical water treatment plant treats stream or river water (turbid surface water with organics) and processes the raw water using various unit processes, including: (1) screening, (2) coagulation, (3) flocculation, (4) sedimentation or settling, (5) filtration, (6) hardness treatment, (7) disinfection, and (8) fluoridation (see Figure 11.2). This chapter provides a brief overview of each of these unit processes, which constitute a typical drinking water treatment system for surface water supplies, in addition to a brief discussion of alternative approaches.

screening Screening (the first important step in treating water containing large solids) is defined as the process whereby relatively large and suspended debris is removed from the water before it enters the plant. River water (the source of water used in our discussion) frequently contains suspended and floating debris varying in size from small rags to logs. Removing these solids is important, not only because these items have no place in potable water but also because this river trash may cause damage to downstream equipment (e.g., clog and damage pumps), may increase chemical requirements, may impede hydraulic flow in open channels or pipes, or may hinder the treatment process (Pankratz, 1995). The most important criteria used in the selection of a particular screening system for water treatment technology are the screen opening size and flow rate. Other important criteria include costs related to operation and equipment, plant hydraulics, debris handling requirements, and operator qualifications and availability. Large surface water treatment plants may employ a variety of screening devices, such as trash screens (or trash rake), traveling water screens, drum screens, bar screens, or passive intake screens. Each of these screening devices is briefly discussed in the following sections.

Trash Screens (Rakes) Trash screens or trash rakes are used to remove rough or large debris retained on a trash rack. They protect pumping equipment and may be used as a preliminary screening device to protect finer screens—drum or traveling water screens, for example. A trash screen consists of one or more stationary trash rakes and a screen raking device. Trash rack bar spacings range from 1.5 to 4 inches and are mostly constructed of steel bars. Those constructed of high-density polyethylene polymers are beginning to replace many of the older steel bar models—these synthetic screens are lighter and less prone to microbial growth, corrosion, and ice. Raking mechanisms are available for use in a variety of intake configurations, including installation on vertical building and

dam walls. Rakes are typically mounted on fixed structures designed to clean a single trash rack, suspended from an overhead gantry, wheelmounted to traverse the entire width of an intake structure and clean individual sections of a wide trash rack, or suspended from an overhead gantry. Traveling Water Screens Traveling water screens (sometimes called bandscreens) are placed in a channel of flowing water to remove floating or suspended debris. These automatically cleaned screening devices protect pumping or other downstream equipment from debris in surface water intakes. Consisting of a continuous series of wire mesh panels bolted to basket frames, or trays, and attached to two matched strands of roller chain, the traveling water screen operates in a vertical path over a sprocket assembly through the flow. As raw water passes through the revolving baskets, debris is collected and retained on the upstream face of the wire mesh panels. The debris-laden baskets are lifted out of the flow and above the operating flow, where a high-pressure water spray directed outward removes the impinged debris. This process can be continuous or intermittent. For intermittent operation, the screen activates when a specified headloss or time elapsed has occurred. When located on a river, traveling water screens may be subject to large fluctuations in flow conditions, debris loading, water depths, and salinity. Depending upon application, the size of the traveling water screen is determined by considering such factors as maximum and average flow; maximum, minimum, and average water levels; wire mesh size; velocity through mesh; basket or channel width; number of screens; type of service; and/or starting and operating headloss requirements. Drum Screens A drum screen (or cylinder screen) has very few moving parts and is mounted on a horizontal axis with a series of wire mesh panels attached or mounted on the periphery of its cylinder. The cylinder slowly rotates on its axis. Because of its simplicity of construction, the maintenance requirements and operating costs of a drum screen installation are usually lower than those of a traveling water screen.

Bar Screens Primarily used in wastewater treatment applications, bar screens are also employed in some water treatment facilities. A bar screen consists of straight steel bars welded at both ends to two horizontal steel members and is automatically cleaned by one or more power operated rakes. As a rake is operated up the face of the bar rack, it removes accumulated debris (usually large solid objects and rags) and elevates in and out of the flow. At the top of the operating cycle of the rake, the debris is swept from the rake into a debris receptacle by a wiper mechanism. When installed in a waterway, the bar screen assembly normally is placed at an angle of 60 to 80 degrees from the horizontal.

Passive Intake Screens Passive intake screens (stationary screening cylinders) have no moving parts and require no debris handling or debris removal equipment. Passive intake screens are placed in a surface water body in such a manner so as to take advantage of natural ambient currents and controlled through-screen velocities to minimize debris buildup. Usually mounted on a horizontal axis and oriented parallel to the natural current flow within the water body, current flow action works to keep the screen clean. Maximum intake velocity of about 0.5 foot per second (fps) is typical and works to minimize debris impingement on the screen surface.

coagulation Coagulation, the second step in water purification, is a unit process that has been used for several years in the treatment of raw water. Basically, coagulation works to settle very fine material of suspended solids. Note: Chemicals employed for coagulation are expected to be safe for drinking water when used according to the American Water Works Association (AWWA) coagulation standards (e.g., Coagulation, Nos. 42402 to 42407).

Coagulants Typically, after screening, raw water is pumped into large settling basins, also known as clar-

ifiers or sedimentation tanks. Within the confines of the settling basin, the screened raw water is allowed to sit for some predetermined time. Although screened, the raw water still contains impurities that may be either dissolved or suspended. The settling basin provides the most convenient way to remove the suspended matter, as it lets the force of gravity do the work. Within the basin, when flow and turbulence are minimal (quiescent conditions), particles more dense than water settle to the bottom of the tank. This process is called sedimentation, and the layer of accumulated solids at the bottom of the tank is called sludge (or biosolids in some wastewater treatment unit processes). The size and density of the suspended particles have a direct bearing on the speed at which they will settle toward the bottom of the basin. The larger or heavier particles will, of course, settle faster than smaller or lighter particles. The forces opposing the downward force of gravity include buoyancy and drag (friction). The particle-settling rate is also affected by the temperature and viscosity of the water.

Note: The nature of the sedimentation process also varies with the concentration of suspended solids and their tendency to interact with one another.

In the sedimentation process just described, not all suspended solids or particles can be completely removed from water, even when given very long detention times. Very small particles called colloids (e.g., bacteria, fine clays, silts) will not settle out of suspension by gravity without some help. This is where coagulants come into play. If we rapidly mix chemical coagulants in the water and then slowly stir the mixture before allowing sedimentation to occur, the colloidal particles will settle. Colloids or finer particles must be chemically coagulated to produce larger floc that is removable in subsequent settling and filtration. The coagulation process (along with flocculation) works to neutralize or reduce the natural repelling electrical force of particles in water, keeping them apart and in suspension. Particles in water usually carry a negative electrical charge. Because all of these particles carry this same negative electrical charge, they repel each other—in the same way that like poles of a magnet do. The object of coagulation (and subsequently flocculation) is to turn the small particles into larger flocs, either as precipitates or suspended particles. These flocs are then conditioned for ready removal in subsequent processes. Stated another way, in this text we define coagulation as a method to alter the colloids so they will be able to approach and adhere to each other to form larger floc particles.

Types of Coagulants Two types of coagulants are used in the coagulation process: coagulants and coagulant aids. Generally, the types of coagulants and aids available are defined by the plant process scheme. To determine optimum chemical dosages for treatment, jar tests are normally used. **Jar Tests** Jar tests are widely used to simulate a full-scale coagulation and flocculation process to determine optimum chemical dosages—the cost-effective dose of a coagulant for the time and intensity of agitation selected. Such tests have been used for many years by the water treatment industry; the test conditions are intended to reflect the normal operation of a chemical treatment facility and allow evaluation of the type and quantity of sludge and physical properties of the floc. The test can be used to

- * Select the most effective chemical.
- * Select the optimum dosage.

Determine the value of a flocculant aid and the proper dose. The testing procedure requires a series of samples to be placed in testing jars and mixed at 100 rpm. Varying amounts of the process chemical or specified amounts of several flocculants are added (one volume/sample container). The mix is continued

for one minute. The mixing slows to 30 rpm to provide gentle agitation, then the floc is allowed to settle. The flocculation period and settling process are observed carefully to determine the floc strength, set-

tleability, and clarity of the supernatant liquor (the water that remains above the settled floc). The supernatant can then be tested to determine the efficiency of the chemical addition for removal of total suspended solids (TSS), biochemical oxygen demand (BOD), and phosphorus. The equipment required for the jar test includes a six-position, variable-speed paddle mixer; six 2-quart wide-mouth jars; an interval timer; and assorted glassware, pipettes, graduates, and so forth.

Coagulation Chemicals Several different chemicals can be used for coagulation. Commonly used metal coagulants are those based on aluminum (aluminum sulfate) and those based on iron (ferric sulfate). The most common coagulant is aluminum sulfate (alum, $\text{Al}_2(\text{SO}_4)_3$). Other common coagulation chemicals are provided in Table 11.1.

Coagulant Aids Coagulation problems often occur because of slow-settling precipitates or fragile flocs that are easily fragmented under hydraulic forces in basins and filters (Hammer and Hammer, 1996). A coagulant aid is a chemical added during coagulation to improve coagulation; to build stronger, more settleable floc; to overcome the effect of temperature drops that slow coagulation; to reduce the amount of coagulant needed; and to reduce the amount of sludge produced (AWWA, 1995). Coagulant aids benefit flocculation by improving the settling qualities and toughness of flocs. Polymers are the most widely used materials. Synthetic polymers are water-soluble, high-molecular-weight organic compounds with multiple electrical charges along a molecular chain of carbon atoms. In drinking water treatment, polymers are extensively used as coagulant aids to build large floc prior to sedimentation and filtration. Other coagulant aids are activated silica, adsorbent weighting agents, and oxidants.

Coagulation Process Operation The common coagulation unit process operation involves the addition of coagulant chemicals by rapid mixing—detention time in the rapid mix tank is typically on the order of minutes (Masters, 1991). During this mixing process, polymer (or some other coagulant aid) is added and blended into the destabilized water prior to flocculation. The removal of impurities by coagulation depends on their nature and concentration, the use of both coagulants and coagulants aids, and characteristics of the water, including pH, temperature, and ionic strength. Because of the complex nature of coagulation reactions, chemical treatment is based on empirical data derived from jar testing or other laboratory tests and field studies (Viessman and Hammer, 1998).

flocculation The destabilized particles and chemical precipitates resulting from coagulation are designed to enhance their settling qualities and thus their removal from water; however, even after coagulation has taken place, these particles and chemical precipitates may still settle very slowly (too slowly). To speed up the settling process, flocculation is employed. Note: Flocculation is the clumping together of the fine particles formed by coagulation. Although the two terms are often used interchangeably, flocculation and coagulation are actually distinct concepts. Flocculation is the most important factor affecting particle-removal efficiency. In water treatment operations, flocculation is a slow mixing process in which the coagulated particles are brought into contact so they will collide, stick together, and grow (agglomerate) to a size that will readily settle. Enough mixing must be provided (e.g., gentle agitation for approximately half an hour) to bring the floc particles into contact with each other and to keep the floc from settling in the flocculation basin. (The heavier the floc and the higher the suspended solids concentration, the more mixing is required to keep the floc in suspension.) The most common type of mixer or flocculator is the paddle type, which uses redwood slats mounted horizontally on motor-driven shafts. Rotating slowly at about one revolution per minute, the paddles provide gentle agitation that promotes floc growth. The rate

of agglomeration or flocculation depends on the number of particles present, the relative volume that they occupy, and the velocity gradient in the basin. Note: The statement that the rate of agglomeration or flocculation depends on velocity gradient refers to the fact that too much mixing can shear the floc particles, tearing them apart again; the floc then becomes smaller and more finely dispersed, a situation we are obviously trying to avoid. For this reason, the velocity gradient must be controlled within a relatively narrow range. The theory of flocculation is complex and beyond the needs of this text, but on an elemental level we can say that flocculation is generally accomplished by slowly rotating, large-diameter mixers. Current practice incorporates dispersion of the coagulant (flash mixing), flocculation, and sedimentation in a single unit called a contact clarifier. Note: Flocculation is the principal mechanism for removing turbidity from water.

Sedimentation In a conventional water treatment plant, the process of coagulation and flocculation precedes the sedimentation process for better results and improved utilization of the settling basins. Sedimentation is then followed by the filtration process. Filtration occasionally may be preceded only by coagulation, in which case filtration is provided after only a few minutes of contact, adding additional stress to the filters. Lack of sedimentation results in less reliable operation of filters when water quality suddenly changes characteristics (DeZuane, 1997). Sedimentation (also known as clarification) is the gravity-induced removal of particulate matter, chemical floc, precipitates from suspension, and other settleable solids. Simply stated, sedimentation separates the liquid from the solids. The process takes place in a rectangular, square, or round tank called a settling or sedimentation tank or basin. Flow patterns within such basins may be rectilinear flow in rectangular basins, radial flow in center-feed settling tanks or square settling tanks, or radial flow or spiral flow in peripheral-feed settling tanks. Sedimentation, in the conventional water treatment process, is typically the step between flocculation and filtration. Design criteria are based on empirical data from the performance of full-scale sedimentation tanks. The common criteria for sizing settling basins are detention time (typically from 1 to 10 hr), overflow rate, weir loading, and, with rectangular tanks, horizontal velocity. In water treatment, the majority of settling basins are essentially upflow clarifiers where the water rises vertically for discharge through effluent channels. More specifically, in the idealized sedimentation tank, water flows horizontally through the basin and then rises vertically, overflowing the weir of a discharge channel at the tank

surface. Floc settles downward, opposite the upflow of water, and is removed from the bottom by a continuous mechanical sludge removal apparatus. The particles with a settling velocity greater than the overflow rate are removed (settled) while lighter flocs are carried out in the effluent. The effluent is then filtered. Note: Sedimentation tanks, either circular or rectangular, are designed for slow, uniform water movement with a minimum of short-circuiting.

Filtration Even after chemical coagulation and sedimentation by gravity, not all of the suspended solids or impurities are removed from water. Nonsettleable floc particles (about 5% of the suspended solids) may still remain in the water, and with only that small percentage left we might ask, "Isn't this good enough?" No, it isn't. This remaining floc would cause problems (including noticeable turbidity), and particles shield microorganisms from the subsequent disinfection processes. The goal of water treatment is to produce potable water that is perceptually crystal clear and that satisfies the Safe Drinking Water Act (SDWA) requirement of 0.5 NTU for turbidity. To accomplish this, an additional treatment step is required that follows coagulation, flocculation, and sedimentation. Filtration (sometimes called a polishing process)

involves the removal of suspended particles from water by passing it through a layer or bed of a porous granular material—sand, for example. As water flows through the filter bed, the suspended particles become trapped within the pore spaces of the filter material (or filter media). When purifying a surface water source (as in the discussion here), filtration is a very important process, even though filtration is only one step in the overall treatment process. Note: Filtration is the process that occurs naturally as surface waters migrate (percolate) through the porous layers of soil to recharge groundwater. This natural filtration removes most suspended matter and microorganisms and is the reason why many wells produce water that does not require any further treatment. The Surface Water Treatment Rule (SWTR) specifies certain filtration technologies. The most common treatment filter systems include rapid gravity filters (either built onsite or packaged plants) and pressure filters. Other types include direct filtration, slow sand filters, and diatomaceous earth (DE) filters. The SWTR also allows the use of alternative filtration technologies, such as cartridge filters.

Filtration treatment unit processes most commonly used in water purification systems include slow or rapid sand filtration, diatomaceous earth filtration, and package filtration systems. Slow and rapid filter systems refer to the rate of flow per unit of surface area. Filters are also classified by the type of granular material used in them. Sand, anthracite coal, coal–sand, multilayered, mixed bed, and diatomaceous earth are examples of different filtering media. Filtration systems may also be classified by the direction the water flows through the medium: downflow, upflow, fine-to-coarse, coarse-to-fine. Finally, filters are commonly distinguished by whether they are gravity or pressure filters. Gravity filters rely only on the force of gravity to move the water down through the grains and typically use upflow for washing (backwashing) the filter media to remove the collected foreign material. Gravity filters are free surface filters commonly used for municipal applications. Pressure filters are completely enclosed in a shell so most of the water pressure in the lines leading to the filter is not lost and can be used to push the water through the filter.

Rapid Filter Systems Slow sand filtration has been used in the United States since 1872. It is still used in many older plants but is not commonly used today in most modern water treatment plants because of various problems associated with this technique. One of the problems is related to the tiny size of the pore spaces in the fine sand, which slows down the water's progress through the filter bed. These filter types also have problems with suspended particles clogging the surface, requiring the filter to be manually scraped clean. These units take up a considerable amount of land area because slow filtration rates require a greater filter surface area to produce the necessary filtered water qualities. In modern water treatment plants, the rapid filter has largely replaced the slow sand filter. The rapid filter consists of a layer of carefully sieved silica sand ranging from 0.6 to 0.75 m in depth on top of a bed of graded gravels. The pore openings between the grains of sand are often greater than the size of the floc particles that are to be removed, so much of the filtration is accomplished by means other than simple straining. Note: The ideal filter medium is coarse enough for large pore openings to retain large quantities of floc, yet sufficiently fine to prevent the passage of suspended solids. It must have adequate depth to allow relatively long filter runs and be graded to permit effective cleaning during backwash.

Adsorption, continued flocculation, and sedimentation in the pore spaces are also important removal mechanisms. When the filter becomes clogged with particles (which occurs approximately once a day, depending on the turbidity of the water), the filter is shut down for a short period of time and cleaned by forcing

water backward through the sand for 10 to 15 minutes. After cleaning, the sand settles back in place and operation resumes.

Other Common Filter Types Rapid flow filters are the most common type used for treating water supplies, primarily because they are the most reliable, but other types of filters are sometimes used to clarify water, including pressure filters and diatomaceous earth filters. A pressure filter is similar to a rapid filter in that the water flows through a granular filter bed; however, instead of being open to the atmosphere and using the force of gravity, the pressure filter is enclosed in a cylindrical steel tank and the water is pumped through the bed under pressure. They are not as reliable as rapid filters, because pressure may force solids through the bed in the effluent. Because of this problem, they are seldom employed in municipal water treatment works but instead are used for filtering water for industrial use or for swimming pools. Diatomaceous earth filters contain a thin layer of a natural, powdery material formed from the shells of diatoms; they are also used primarily for industrial or swimming pool applications because they are not as reliable as rapid sand filters.

Hardness treatment Two commonly used methods to reduce hardness are the lime-soda process and ion exchange. The lime-soda process is applicable for large facilities, whereas ion exchange is normally employed in smaller water works. The lime-soda process will not remove all of the hardness and is usually operated to produce a residual hardness of about 100 mg/L as CaCO_3 . Greater reductions are not economical and may have adverse health consequences as well (McGhee, 1991). The discussion in this text focuses on ion exchange. Ion exchange is accomplished by charging a resin with sodium ions and allowing the resin to exchange the sodium ions for calcium or magnesium ions. Common resins include zeolites—natural and manmade minerals that will collect from a solution certain ions (sodium or KMnO_4), and either exchange these ions (in the case in water softening) or use the ions to oxidize a substance (in the case of iron or manganese removal). The negative side of using ion exchange is that, even though the process softens water by removing all (or nearly all) of the hardness and adds sodium ions to the water, the water may be more corrosive than before. The addition of sodium ions to the water may also increase the health risk of those with high blood pressure.

Disinfection At the turn of the last century, 35,000 people per 1,000,000 people did not reach 20 years of age. Today, however, the rate of births exceeds the rate of deaths, and the average lifespan is much longer. Curbing waterborne disease through disinfection has made a significant contribution to birth rates outpacing death rates worldwide. The Safe Drinking Water Act requires that public water supplies be disinfected, and the U.S. Environmental Protection Agency (USEPA) sets standards and establishes processes for the treatment and distribution of disinfected water to ensure that no significant risks to human health occur. The USEPA Science Advisory Board has ranked pollutants in drinking water as one of the highest health risks meriting the Agency's attention because of large-scale population exposure to contaminants, including lead, disinfectants and disinfection byproducts (DBPs), and disease-causing organisms. Disinfectants are used by virtually all surface water systems in the United States and by an unknown percentage of systems that rely on groundwater. For nearly a century, chlorine has been the most widely used and most cost-effective disinfectant; however, disinfection treatments can produce a wide variety of byproducts, many of which have been shown to cause cancer or other toxic effects. Recently, concern has been raised over water quality deterioration, a problem that can grow dramatically during distribution unless systems are properly designed and operated. Disinfection is an integral part of water treatment, but filtration prior

to disinfection is necessary to reduce pathogen levels and make disinfection more reliable by removing turbidity and other interfering constituents. To solve the disinfectant and disinfection byproducts problem, we need innovative upgrades for the existing techniques, as well as new approaches to address these problems. Areas of interest include

- Alternatives to chlorine disinfection for removing pathogenic microorganisms, including innovative applications of ultraviolet (UV) radiation and processes that improve overall effectiveness while using reduced amounts of disinfectant
- Development of innovative unit processes, particularly for small systems, for removal of organic and inorganic contaminants (such as arsenic), particulates, and pathogens, such as cyst-like organisms and emerging pathogens such as caliciviruses, microsporidia (septata and enterocytozoan), hepatitis A virus, *Mycobacterium avium*–intracellulare complex (MAC), *Helicobacter pylori*, *Legionella pneumophila*, adenovirus 40/41/1-39, and *Toxoplasma gondii*
- Development of efficient, cost-effective treatment processes for removing disinfection byproduct precursors (e.g., trihalomethanes, haloacetic acids), for ozonation (bromate, aldehydes), for chlorination (chloropicrin, haloacetonitriles), and for chloramination (organic chloramines, cyanogen chloride)
- Improved methods for controlling pathogens through coagulation/settling, filtration, or other cost-effective means
- Drinking water contamination control between the treatment plant and the user, especially considering potential chemical leaching from distribution system materials and surfaces (e.g., lead, copper, iron, and other pipe materials; protective coatings) as a result of instability, interaction with microorganisms, disinfection agents, and water treatment chemicals

The unit processes described thus far—screening, coagulation, flocculation, sedimentation, and filtration—together comprise a type of treatment called clarification. Along with removing turbidity and suspended solids, clarification also removes many microorganisms from the water; however, clarification by itself is not sufficient to ensure the complete removal of pathogenic bacteria and viruses. Earlier it was stated that one of the primary goals of water treatment is to treat raw water to the point where it is possible to deliver to the consumer a water product that is perceptually crystal clear. Obviously, the consumer does not want to drink a glass full of mud, a glass full of slime, a glass full of metal-colored, foul-smelling water—or even a glass of water that looks like it was dipped from a creek. Would you? The point is, when the water has been treated to the point of crystal clarity, the treatment process must be taken a step further—to the point where the water is completely free of disease-causing microorganisms. To accomplish this, the final treatment process in water treatment plants occurs—disinfection, which destroys or inactivates pathogens.

Key Disinfection Terms* Before moving on to a discussion of the major disinfection methods used in treating water for human consumption, it is necessary to first define a few pertinent terms related to disinfection in general. To begin with, let's establish the distinction between primary and secondary disinfection:

- Primary disinfection—Initial killing of *Giardia* cysts, bacteria, and viruses
- Secondary disinfection—Maintenance of a disinfectant residual that prevents regrowth of microorganisms in the water distribution system between treatment and consumer

Other terms the reader should understand include

- Disinfection—Inactivation of virtually all recognized pathogenic microorganisms, but not necessarily all microbial life (which would be considering pasteurization or sterilization).
- Disinfectant—(1) Any oxidant, including but not limited to, chlorine, chlorine dioxide, chloramine, and ozone, added to water in any part of the treatment or distribution process that is intended to kill or inactivate pathogenic microorgan-

isms. (2) A chemical or physical process that kills pathogenic organisms in water; chlorine is often used to disinfect sewage treatment effluent, water supplies, wells, and swimming pools. • Disinfectant time—The time required for water to move from one point of disinfectant application (or the previous point of residual disinfectant measurement) to a point before or at the point where the residual disinfectant is measured. • Disinfectant contact time (T in $C \times T$ calculation)—The time (in minutes) required for water to move from the point of disinfectant application or the previous point of disinfection residual measurement to a point before or at

- Adapted from Spellman, F.R., *Disinfection Alternatives*, Technomic, Lancaster, PA, 1999.

the point where residual disinfectant concentration (C) is measured. Where only one C is measured, T is the time (in minutes) required for water to move from the point of disinfectant application to a point before or at where residual disinfectant concentration (C) is measured. Where more than one C is measured, T is defined as follows: • For the first measurement of C, the time (in minutes) required for water to move from the first or only point of disinfectant application to a point before or at the point where the first C is measured • For subsequent measurements of C, the time in minutes that water takes to move from the previous C measurement point to the C measurement point for which the particular T is being calculated • Disinfection byproduct—A compound formed by the reaction of a disinfectant such as chlorine with organic material in the water supply. • Presence or absence of coliforms—Presence of coliform bacteria in water is an indication that the water may be contaminated by pathogenic organisms. Absence of coliform bacteria is considered to be sufficient evidence that pathogens are absent—if the source is good, a chlorine residual level is maintained and the supply has a good history. • Sterilization—The destruction of all microorganisms. Sterilizing potable water requires the application of a much higher dose of chemical disinfectants, which would greatly increase operating costs and would create taste problems for the consumer. Excessive application of disinfectants also generates excessive levels of unwanted disinfection byproducts. For these reasons, current treatment practices are used for turbidity removal and subsequent disinfection to the extent necessary to eliminate known diseasecausing organisms sufficient to protect public health. Note: Sterilization should not be confused with disinfection. • Waterborne disease—Caused by pathogenic organisms in water.

Disinfection Methods Although chlorination is the best known and the most common disinfection method, other methods are available and can be used in various situations. The three general types of disinfection are • Heat treatment—Probably one of the first methods employed to disinfect water was to boil it. For small quantities of water, boiling water is still a good emergency procedure to use. • Radiation treatment—Uses ultraviolet radiation to disinfect water.

- Chemical treatment—Employs the use of chemicals to disinfect water. Examples of chemical disinfectants include oxidizing agents such as chlorine, ozone, bromine, iodine, and potassium permanganate; metal ions such as silver, copper, and mercury; and acids and alkalis.

Obviously, several different disinfectants are available for use in treating water, and several of these are discussed in detail in subsequent sections. For now, it is important to understand that, even though several choices are available, whichever disinfectant is chosen must meet certain criteria—more specifically, the disinfectant chosen must be effective for disinfecting water (and wastewater) and must possess certain desirable characteristics. Desirable Characteristics of a Disinfectant 1. It must act in a reasonable time. 2.

It must act as temperature or pH changes. 3. It must be nontoxic. 4. It must not add unpleasant taste or odor. 5. It must be readily available. 6. It must be safe and easy to handle and apply. 7. It must be easy to determine the concentration of. 8. It must be able to provide residual protection. 9. Pathogenic organisms must be more sensitive to the disinfectant than are nonpathogens. 10. It must be capable of being applied continually. 11. The amount applied must be sufficient to produce a safe water.

In addition to the desirable characteristics of a disinfectant listed above, the disinfectant chosen must be able to kill off or deactivate pathogenic microorganisms by one of several possible methods, including: (1) damaging the cell wall, (2) altering the ability to pass food and waste through the cell membrane, (3) altering the cell protoplasm, (4) inhibiting the cells' conversion of food to energy, or (5) inhibiting reproduction.

Chlorination For the past several decades, chlorine dispensed as a solid (calcium hypochlorite), liquid (sodium hypochlorite), or gas (elemental chlorine, Cl_2) has been the disinfectant of choice, particularly in the United States. Chlorine (sometimes referred to as the workhorse of disinfection) has proven its worth both because of its effectiveness and because it is relatively inexpensive; it also provides a chlorine residual in the water distribution system, ensuring that the water remains disease free. Gaseous chlorine (Cl_2), 2.5 times as heavy as air, is a greenish-yellow toxic gas. One volume of liquid chlorine confined in a container under pressure yields about 450 volumes of gas. Large water treatment works usually use chlorine gas, supplied in liquid form, in high-strength, high-pressure steel cylinders. The liquid immediately vaporizes in the form of gas when released from these pressurized containers. Chlorine gas is lethal at concentrations as low as 0.1% air by volume. In nonlethal concentrations, it irritates the eyes, nasal membranes, and respiratory tract.

Sodium hypochlorite is most commonly used in smaller systems, because it is simpler to use and has less extensive safety requirements than gaseous chlorine; in the form used, it is less toxic. Recently, many larger water facilities that have used chlorine for disinfection are beginning to substitute sodium hypochlorite for chlorine because of regulatory pressure. Note: The Occupational Safety and Health Administration's Process Safety Management Standard (29 CFR 1910.119) and USEPA's Risk Management Program (Clean Air Act, Section 112(r)(7)) have come to be known in the industry as the "chlorine killers," because of their effect on industrial processes. The USEPA is attempting to steer industry away from the use of chlorine. Although the Agency cannot absolutely outlaw this substance from use, it is following the path of simply regulating it to death. In an effort to avoid having to comply with strict (in some cases, unworkable) regulations, many water treatment and wastewater facilities in the United States are substituting some other chemical product that is not regulated (at least for the moment) such as sodium hypochlorite. Sodium hypochlorite provides 5 to 15% available chlorine (common laundry bleach is a 5% solution of sodium hypochlorite). Usually diluted with water before application as a disinfectant, it is very corrosive and should be handled and stored with care and kept away from equipment that can be damaged by corrosion. Sodium hypochlorite solution is more costly per pound of available chlorine and does not provide the same level of protection of chlorine gas.

Calcium hypochlorite is a white solid in granular, powdered, or tablet form containing 65% available chlorine. In packaged form, calcium hypochlorite is stable—more stable than solutions of sodium hypochlorite, which deteriorate over time; however, calcium hypochlorite is hygroscopic, which means it readily absorbs moisture. It reacts slowly with moisture in the air to form chlorine gas. It is a corrosive material

with a strong odor and requires proper handling. Some practical difficulty is involved in dissolving calcium hypochlorite. It must be kept away from organic materials such as wood, cloth, and petroleum products.

Reactions between it and organic materials can generate enough heat to cause a fire or explosion.

Chlorine Use Whatever form of chlorine is used for disinfection (elemental chlorine, sodium hypochlorite, or calcium hypochlorite), it may be added to the incoming flow (prechlorination) to assist with the oxidation of inorganics or to arrest biological action that may produce undesirable gases in the bottom of clarifiers. More often, however, chlorine is added just prior to filtration to keep algae from growing at the medium surface and to prevent large populations of bacteria from developing within the filter medium. Safe and effective application of chlorine requires specialized equipment and considerable care and skill on the part of the plant operator. Various means of feeding chlorine have been developed, but probably one of the widest used and safest types of chlorine feed devices is the all-vacuum chlorinator. Mounted directly on the chlorine cylinder, the gaseous chlorine is always under a partial vacuum in the line that carries it to the point of application. In a typical vacuum chlorine feed system, the vacuum is formed by water flowing through the ejector unit at high velocity.

Hypochlorites are usually applied to water in liquid form by means of positive displacement-type pumps, which deliver a specific amount of liquid on each stroke of a piston or flexible diaphragm. Chlorine, when added to water, reacts with various substances or impurities in the water (e.g., organic materials, sulfides, ferrous iron, nitrites), which creates a chlorine demand. Chlorine demand is a measure of the amount of chlorine that will combine with impurities and is therefore available to act as a disinfectant. Chlorine combines with ammonia or other nitrogen compounds to form chlorine compounds that have some disinfectant properties. These compounds are called combined available chlorine residual. In the context used here, “available” means available to act as a disinfectant. The uncombined chlorine that remains in the water after combined residual is formed is called free available chlorine residual. Free chlorine is a much more effective disinfectant than combined chlorine.

Factors Affecting Successful Chlorination The factors important to successful chlorination are

- Concentration of free chlorine
- Contact time
- Temperature
- pH
- Turbidity

The effectiveness of chlorination is directly related to the contact time with and concentration of free available chlorine. At lower chlorine concentrations, contact times must be increased. Maintaining a lower pH will also increase the effectiveness of disinfection. The higher the temperature, the faster the disinfection rate. Chlorine (or any other disinfectant for that matter) is effective only if it comes into contact with the organisms to be killed. Good contact between chlorine and microorganisms is prevented whenever high turbidity levels exist. For this and aesthetic reasons, turbidity should be reduced where necessary through the coagulation and sedimentation methods previously discussed.

Chlorination Byproducts A serious disadvantage of chlorination is the potential formation of byproducts. Chlorine, for example, can mix with the organic compounds in water (such as decaying vegetation) to form trihalomethanes (THMs). One THM, chloroform, is a suspected carcinogen. Other common trihalomethanes are similar to chloroform and may cause cancer. At the present time, about 90% of U.S. water utilities use chlorine to disinfect water. Although chlorine has virtually eliminated the risks of waterborne disease such as typhoid fever, cholera, and dysentery, recent studies have shown risks associated with byproducts of chlorine—a reason why water utilities already have been looking at alternative methods for disinfecting water. Several approaches for reducing harmful chlorination byproducts have been used. For example, one approach is to

remove more of the organics before any chlorination takes place. This can be accomplished (to a degree) by not chlorinating the incoming

raw water before coagulation and filtration, thus reducing the formation of THMs. Aeration or adsorption on activated carbon will remove organic materials at higher concentrations or those not removed by other techniques. Another approach is to reevaluate the amount of chlorine used—the same degree of disinfection might be possible with lower chlorine dosages. Changing the point in treatment where chlorine is added is another approach commonly employed; rather than adding chlorine as chemical feed during coagulation, sedimentation, or filtration, it can instead be added after filtration. Another current approach is using alternative disinfection methods. Note: Because of OSHA's Process Safety Management (PSM) standard and USEPA's Risk Management Program (RMP), many facilities currently using elemental chlorine have used or are actively pursuing the use of alternative disinfection methods. We further reemphasize that the problem of THMs is also helping spur interest in alternatives to chlorination as the preferred method of disinfection.

Alternative Disinfection Methods Currently, several alternative disinfection methods are available for use in treating water, but the following discussion focuses on two of these alternatives: ozonation and ultraviolet (UV) radiation. These commonly used alternatives (especially in small water treatment systems) are also increasingly being substituted for existing chlorination systems at larger plants because of regulatory pressure. Note: Before discussing the ozonation and ultraviolet disinfection alternatives, it is important to point out that neither one of these two alternative disinfectants is an easy solution to problems created by chlorination. It is true that each has the advantages of not creating THMs and not being covered by the requirements under the PSM standard and RMP, but each has uncertainties and known disadvantages that have restricted their more widespread use. In addition, ozonation and ultraviolet irradiation cannot be used as disinfectants by themselves. Both require secondary disinfectant (usually chlorine) to maintain a residual in the distribution system.

Ozonation Ozone (O_3), a gas at ordinary temperature and pressures, is a very powerful disinfectant that breaks up molecules in water; it is even more effective against some viruses and cysts than chlorine. It has the added advantage of leaving no taste or odor and is unaffected by pH or the ammonia content of the water. When ozone reacts with reduced inorganic compounds and with organic material, an oxygen atom instead of a chloride atom is added to the organics, the end result being an environmentally acceptable compound. But, because ozone is unstable and cannot be stored, it must be produced onsite. Ozonation usually costs more than chlorination. **Ultraviolet** Ultraviolet (UV) light is electromagnetic radiation just beyond the blue end of the light spectrum, outside the range of visible light. It has a much higher energy level than visible light, and in large doses it inactivates both bacteria and viruses. UV energy is absorbed by genetic material in the microorganisms, interfering with their ability to reproduce and survive, as long as the radiation contacts the microorganisms without interference from turbidity. The big advantage of UV disinfection over chlorine and

ozone is that UV does not involve chemical use. Generally, UV light used for disinfecting water is generated by a series of submerged, low-pressure mercury lamps. Continuing advances in UV germicidal lamp technology are making UV disinfection a more reliable and economical option for disinfection in many plants.

NONCONVENTIONAL WATER TREATMENT TECHNOLOGIES Stage 1 of the USEPA's Disinfectants

and Disinfection Byproduct Rule and the Interim Enhanced Surface Water Treatment Rule, designed to significantly lower THM byproducts of chlorine disinfection in water, has driven (along with the regulatory requirements of the PSM standard and RMP) many water and wastewater treatment utilities to find and use alternative disinfection methodologies. Although ozonation and ultraviolet irradiation might be suitable disinfection alternatives, switching from chlorine to chlorine dioxide (a chemical that has been proven to form fewer THMs) might also be another viable disinfection alternative. Whichever disinfection alternative is ultimately selected, remember that the selection is driven not only by regulatory requirements but also by site-specific requirements. The disinfection issues covered to this point are important—the overall ramifications of regulatory pressure and environmental impact cannot be overstated—but other issues besides disinfection must be considered when deciding which water treatment methodology to employ. Most of the time, clarification by coagulation, flocculation, sedimentation, and filtration removes suspended impurities and turbidity from drinking water, and disinfection (the final step in the process) produces potable water, free of harmful pathogens. Simply put, the water treatment processes discussed in the previous sections of this part of the text are usually sufficient to render most natural surface water (such as a river) potable. In some instances, however, the water supply may contain materials that are not removed by conventional water treatment processes, and other treatment processes may be required to remove many of the dissolved organic and inorganic substances. Examples would include groundwater with excessive dissolved solids and surface waters containing organic compounds from domestic or industrial wastewaters or organics occurring naturally such as humic acid or products of algae blooms. Additional processes are available for removing these contaminants. Note: These additional water treatment processes involve sophisticated equipment and require highly skilled operators; therefore, they are quite expensive (Peavy et al., 1985). Additional water unit treatment processes may be used in addition to clarification or applied separately, depending on the source and quality of the raw water. Let's take a closer look at groundwater. The question is—does a typical groundwater source require treatment beyond conventional means? The answer is that groundwater does not normally require processing by the unit treatment steps listed above, other than disinfection, because groundwater is filtered naturally by the layers of soil from which it is withdrawn. Disinfection is only applied (in many cases) as a precautionary step required by law for public water systems. Groundwater is usually free of bacteria or other microorganisms; however, that all groundwater comes into contact with soil and rock is a cause for concern. With such contact, groundwater may become contaminated by high levels of dissolved minerals that must be removed.

FLUORIDATION Fluoride, when added to drinking water supplies in small concentrations (about 1.0 mg/L), can be beneficial. In some locations, common practice is to mix a 4% solution of sodium fluoride and feed that into the flow of the water system. The amount that is fed depends on the air temperature and on the fluoride levels in the raw water. Experience has shown that drinking water containing a proper amount of fluoride can reduce tooth decay by 65% in children. Fluoride combines chemically with tooth enamel when permanent teeth are forming, and the result is teeth that are harder, stronger, and more resistant to decay. The USEPA sets the upper limits for fluoride in drinking water supplies based on ambient temperatures; for example, people drink more water in warmer climates, so fluoride concentrations should be lower in these areas.

WATER TREATMENT OF ORGANIC AND INORGANIC CONTAMINANTS Manmade compounds

that contain carbon—synthetic organic chemicals (SOCs)— are, from time to time, detected in U.S. water supplies. Some of these are volatile organic chemicals (VOCs), such as the solvent trichloroethylene. The problem with VOCs in a water supply (i.e., any water supply used by the public) is twofold. They are easily absorbed through the skin and they volatilize into gases that can then be inhaled by those taking a shower or a bath or while washing dishes. How do water supplies become contaminated by organic compounds? Good question. Basically, sources of organic contaminants are usually improperly disposed wastes, pesticides, industrial effluents, and leaking fuel oil tanks (gasoline in particular). Water supplies may also contain inorganic contaminants consisting mainly of substances occurring naturally in the ground, such as sulfate, fluoride, arsenic, barium, radium, selenium, and radon. Metallic substances from industrial sources can contaminate surface waters. The inorganic ion nitrate (from fertilizers and feedlot runoff in agricultural areas) occurs frequently in groundwater supplies. Another source of inorganic chemical contamination in drinking water supplies is corrosion or deterioration of water supply equipment, such as plumbing systems, which release metal and nonmetal substances into the water, including lead, cadmium, zinc, copper, iron, and plumbing cement. Inorganic contaminants can be treated by corrosion controls and removal techniques. Corrosion controls reduce the presence of corrosion byproducts (e.g., lead) at the consumer's tap. Removal technologies, coagulation and filtration, reverse osmosis, and ion exchange are used to treat source water that is contaminated with metals or radioactive substances. The following sections discuss processes for removing inorganic and organic dissolved solids from water intended for potable use. Keep in mind that (with some modifications) these same processes may act as tertiary treatment for wastewater.

aeration Aeration (air stripping) is a physical treatment process in which air is thoroughly mixed with water—a technique effective for removing dissolved gases and highly volatile odorous compounds. Contact with air and oxygen can improve water quality in a number of ways. When aeration is a first step in processing well water, for example, it may achieve any or all of the following: removal of hydrogen sulfide, reduction of dissolved carbon dioxide, and addition of dissolved oxygen for oxidation of iron and manganese (the oxygen in the air reacts with the iron and manganese to form an insoluble precipitate—rust). One of the most common uses of aeration is for taste and odor control. Sedimentation and filtration are then necessary to clarify the water. Note: Aeration is rarely effective in processing surface waters, simply because the odor-producing substances are generally nonvolatile. Several methods to aerate the water are available. The method selected depends primarily on the type and concentration of material to be removed from the water and on the available pressure. Aeration in water treatment can be accomplished using spray nozzles, cascade systems, multiple-tray aerators, diffused-air aerators, and mechanical aerators.

oxidation Simply stated, oxidation is a reaction in which a substance loses electrons, thus increasing its charge. A substance that oxidizes another is referred to as an oxidizing agent or oxidizer. In water treatment, oxidation is used to remove or destroy undesirable tastes or odors, to aid in removal of iron and manganese, and to help improve clarification and color removal in source water. Chlorine dioxide, potassium permanganate, and ozone are strong oxidants capable of destroying many odorous compounds. Because they do not produce THMs, these chemicals are favored over heavy chlorination. Note: Atmospheric oxygen, through aeration, can be used to oxidize the organic substances responsible for undesirable tastes and odors, but the process is usually too slow to be of value. If dissolved gases such as hydrogen sulfide are the cause of taste and odor problems, aeration will effectively remove them through oxidation and

stripping.

Adsorption When we speak of adsorption, we are referring primarily to a surface phenomenon—the adsorption that results when one substance attaches itself to the surface of another. The two most common adsorptive media used in water treatment are activated carbon and activated alumina. These adsorptive materials are generally most effective for taste and odor control and for removal of organic pollutants; however, the most important applications of adsorption in water treatment are the removal of arsenic and organic pollutants.

Adsorption of organic materials using activated carbon has been a common practice in water treatment for many years. Activated carbon is manufactured from carbonaceous material such as wood, coal, and petroleum residues. A char is made by burning the material in the absence of air, and it is then oxidized at higher temperatures to create a very porous structure. This activation step provides irregular channels and pores in the solid mass, resulting in a very large surface-area-to-mass ratio. This large surface area gives activated carbon its effectiveness as an adsorbing agent. The larger the surface area of an adsorber, the greater its power. Each activated carbon contains a huge number of pores and crevices into which organic molecules enter and are adsorbed onto the activated carbon surface. Activated carbon has a particularly strong attraction for organic molecules such as the aromatic solvents benzene, toluene, and nitrobenzene; the chlorinated aromatics polychlorinated biphenyls (PCBs), chlorobenzenes, and chloronaphthalene; phenol and chlorophenols; the polynuclear aromatics acenaphthene and benzopyrenes; pesticides and herbicides; chlorinated aliphatics such as carbon tetrachloride and chloroalkyl ethers; and high-molecular-weight hydrocarbons such as dyes, gasoline, amines, and humics. Two forms of activated carbon are used in water treatment: powdered and granular. Powdered activated carbon is often used for taste and odor control. Its effectiveness depends on the source of the undesirable tastes and odors. It is also effective in removing the organic precursors that react with chlorine to form harmful THM compounds after disinfection. Powdered activated carbon is a finely ground, insoluble black powder that can be added at any point in the treatment process ahead of the filters. It is fed to water either as a dry powder or as a wet slurry. Although adsorption is nearly instantaneous, a contact time of 15 minutes or more is desirable before sedimentation or filtration. Activated carbon media must periodically be replaced with new or regenerated activated carbon. Replacement cycles can vary from 1 to 3 years for taste and odor treatment to as little as 4 or 5 weeks for removal of organics. The activated carbon regeneration process involves (1) removing the spent carbon as a slurry, (2) dewatering the slurry, (3) feeding the carbon into a special furnace where regeneration occurs (i.e., the organics are driven from the carbon surface by heat), and (4) returning it to use. Activated alumina (a highly porous and granular form of aluminum oxide) is also an adsorptive medium used in water treatment. It is used primarily to remove arsenic and excess fluoride ions. Water is percolated through a column of alumina media, and a combination of adsorption and ion exchange performs the actual removal of arsenic and fluoride ions. Like the regeneration process used to restore used activated carbon to full potency, activated alumina also requires periodic regeneration, accomplished by passing a caustic soda solution through the media. Excess caustic soda is neutralized by rinsing the activated alumina with an acid. Disposal of these wash waters, laden with toxic arsenic and fluoride ions, must be done in accordance with applicable laws. Note: Powdered activated carbon is much more difficult to regenerate than granular activated carbon. Granular activated carbon is sometimes used in the filter bed itself, combining both filtration and adsorption in one treatment unit. The major problem associated

with granular activated carbon systems is suspended solids in the water plugging up the bed.

Demineralization Demineralization refers to the removal of dissolved solids (inorganic mineral substances) from water. Dissolved solids contain both cations and anions and therefore require two types of ion exchange resins. Cation exchange resins used for demineralization purposes have hydrogen exchange sites and are divided into strong acid and weak acid classes. The anion exchange resins commonly used contain hydroxide ions and are divided into strong and weak base classes. Demineralization is commonly used in industry in waste treatment for removal of arsenic, barium, cadmium, chromium, fluoride, sulfate, and zinc. Some general advantages of using ion exchange to remove these contaminants are the low capital investment required and the mechanical simplicity of the process. In addition, the ion exchange process can be used to recover valuable chemicals for reuse, or harmful ones for disposal. For example, it is often used to recover chromic acid from metal finishing waste for reuse in chromeplating baths. It also has some application in the removal of radioactivity. The major disadvantages are the high chemical requirements needed to regenerate the resins and to dispose of chemical wastes from the regeneration process. These factors make ion exchange more suitable for small systems than for large ones.

membrane processes Membrane processes used in water treatment are primarily demineralization processes. Demineralization of water can be accomplished using thin, microporous membranes. Electrodialysis and reverse osmosis are the most common membrane processes. Before we briefly discuss these two membrane processes, you need a basic understanding of osmosis. During osmosis, two solutions containing different concentrations of minerals are separated by a semipermeable membrane. Water tends to migrate through the membrane from the side of the more dilute solution to the side of the more concentrated solution. This is osmosis, and it continues until the build-up of hydrostatic pressure on the more concentrated solution is sufficient to stop the net flow. In reverse osmosis, the flow of water through the semipermeable membrane is reversed by applying external pressure to offset the hydrostatic pressure. This results in a concentration of minerals on one side of the membrane and pure water on the other side. Reverse osmosis can treat for a wide variety of health and aesthetic contaminants in water. Effectively designed, reverse osmosis equipment can treat aesthetic contaminants that cause unpleasant taste, color, and odor problems, such as a salty or soda taste caused by chlorides or sulfates. Reverse osmosis can also be effective for treating arsenic, asbestos, atrazine, fluoride, lead, mercury, nitrate, and radium. When used with appropriate carbon prefiltering, additional treatment can also be provided for such “volatile” contaminants as benzene, trichloroethylene, trihalomethanes, and radon. Some reverse osmosis equipment is also capable of treating for *Cryptosporidium*. Reverse osmosis can be expected to play a major role in water treatment for years to come. Reverse osmosis (also called ultrafiltration) is the most common process for reducing the salinity of brackish groundwater. In operation, a semipermeable membrane (the most essential element in the reverse osmosis method of demineralization)

separates salty water of two different concentrations. Concentrations have a natural tendency to become equalized by a flow of water from the dilute side to the concentrated side (osmosis). But high pressure applied to the high concentration side of the membrane can reverse this direction of flow. Freshwater diffuses through the membrane, leaving a more concentrated salt solution behind. The performance of reverse osmosis units is highly dependent on a number of water quality parameters. Suspended solids, dissolved organics, hydrogen sulfide, iron, and strong oxidizing agents (chlorine, ozone, and permanganate) are harmful to membranes. Electrodialysis is the demineralization of water using the principles of osmosis—but it

uses ion-selective membranes and an electric field to separate anions and cations in solution. In the past, electrodialysis was most often used for purifying brackish water, but it is now finding a role in industrial waste treatment as well. For example, metals salts from plating rinses are sometimes removed in this way. A PARADIGM SHIFT IN PROGRESS Water shortage is the lack of adequate accessible water resources to meet water needs within a locality. More than 1.2 billion people lack access to clean drinking water (United Nations, 2017). For localities where access to drinking water is readily available, an issue that is not necessarily recognized at this time is the one-and-done scenario discussed earlier—that is, safe drinking water quality water is drawn from a tap and used for a variety of purposes and that is that. After being used, this water is poured down drains or flushed down toilets—out of sight and out of mind. But, a significant paradigm shift is beginning to occur. The idea of toilet-to-tap reuse is not palatable to many people, but we need water. We cannot live without water. Fortunately, we can clean used water and reuse it, a task that Mother Nature often can do for us naturally. We have no other choice. Regions where water is readily accessible today may not be able to brag about that in the future. Population growth, overuse, misuse, abuse, and other events and actions affect water use and have detrimental impacts on water quality. We need to change the one-and-done scenario to a one-and-redone scenario by using technology to purify used water. The use of advanced treatment and purification of used water (wastewater) to drinking water quality is a paradigm change in progress.

ADVANCED TREATMENT OF WASTEWATER TO DRINKING WATER QUALITY Advanced technologies and processes used for wastewater treatment and purification provided at indirect potable reuse (IPR) plants varies (see Figure 11.3) but are typically focused on providing multiple barriers for the removal of pathogens and organics. Nitrogen and TDS removal is provided at some locations where necessary. Table 11.2 shows most of the indirect potable reuse projects that have been implemented in the United States. The table has been sorted according to the type of potable reuse application (i.e., direct aquifer injection, aquifer recharge with surface spreading, and surface water augmentation). The first five projects shown in this table are direct injection

projects that match the proposed HRSD concept. Water extracted from direct injection and surface spreading projects that recharge groundwater is not typically treated again prior to distribution into the potable water system; however, water from surface water augmentation projects is typically treated again at water treatment plants because of water treatment requirements stipulated by the USEPA's Surface Water Treatment Rule (SWTR). For example, Fairfax County's Griffith Water Treatment Plant provides coagulation, sedimentation, ozone oxidation, biological activated carbon filtration, and chlorine disinfection for water extracted from the Occoquan Reservoir that is augmented by the Upper Occoquan Service Authority's indirect potable reuse plant. As shown in Table 11.2, the treatment provided for indirect potable reuse projects is typically a combination of multiple barriers for the removal of pathogens and organics. Multiple barriers for pathogens are typically provided through a combination of coagulation, flocculation, sedimentation, lime clarification, filtration (granular or membrane), and disinfection (chlorine, ultraviolet, or ozone). Multiple barriers for organics removal are typically provided through a combination of advanced treatment processes (e.g., reverse osmosis, granular activated carbon, ozone in combination biological activated carbon), although conventional treatment processes (e.g., coagulation, softening) also provide removal at some locations. All potable reuse plants listed in Table 11.2 include a robust organics removal process of granular activated carbon (GAC), granular media filtration (GMF), biological activated car-

bon (BAC), reverse osmosis (RO), microfiltration (MF), ultraviolet advanced oxidation process (UVAOP), membrane bioreactor (MBR), or soil aquifer treatment (SAT), which are effective barriers to bulk and trace organics and represent the backbone of the potable treatment process. SAT is the controlled application of wastewater to earthen basins in permeable soils at a rate typically measured in terms of meters of liquid per week. The purpose of a soil aquifer treatment system is to provide a receiver aquifer capable of accepting liquid intended to recharge shallow groundwater, and system design and operating criteria are developed to achieve that goal. However, there are several alternatives with respect to the utilization or final fate of the treated water (USEPA, 2006):

- Groundwater recharge
- Recovery of treated water for subsequent reuse or discharge
- Recharge of adjacent surface streams
- Seasonal storage of treated water beneath the site with seasonal recovery for agriculture

The SAT process typically includes application of the reclaimed water using spreading basins and subsequent percolation through the vadose zone. SAT provides significant removal of both pathogens and organics through biological activity and natural filtration. However, because some aquifers are confined, it is not possible to utilize the SAT for treatment through the vadose zone to recharge them. On the other hand, movement of reclaimed water through the aquifer after direct injection will provide significant treatment benefits, including excellent removal of pathogens. Advanced water treatment plants based on reverse osmosis and granular activated carbon are often utilized at locations where SAT treatment through the vadose zone is not feasible, because it is possible for these processes to be implemented at most locations. As a case in point, consider that in the Hampton Roads region of Chesapeake Bay in 1607, when Captain John Smith and his team settled in Jamestown, oysters up to 13 inches in size were plentiful—more than could ever be harvested and consumed by the handful of early settlers. This population of oysters and other aquatic lifeforms remained plentiful until the population gradually increased in the Bay region. Overharvesting of oysters by the increased numbers of humans living in the Chesapeake Bay region has been a major factor in the decline of the oyster population; however, the real culprit is pollution. Before the Bay became polluted by sewage, sediment, and garbage, oysters could handle natural pollution from stormwater runoff and other sources. It has been estimated that a century ago, when there was a much larger oyster population than today, the oyster population could filter pollutants from the Bay and clean it up in as little as 4 days. By the 1930s, however, the declining oyster population was overwhelmed by the increasing pollution levels. For years, the author has stated that pollution is a judgment call. Why a judgment call? Because people's opinions differ as to what they consider to be a pollutant based on their assessment of benefits and risks to their health and economic wellbeing. For example, visible and invisible chemicals spewed into the air or water by an industrial facility might be harmful to people and other forms of life living nearby, but if the facility is required to install expensive pollution controls it might have to shut down or move away. Workers who would lose their jobs and merchants who would lose their livelihoods might feel that the risks posed by polluted air and water are minor weighed against the benefits of profitable employment. The same level of pollution can also affect two people quite differently. Some forms of air pollution, for example, might cause a slight irritation for a healthy person but cause life-threatening problems for someone with chronic obstructive pulmonary disease, such as emphysema. Differing priorities lead to differing perceptions of pollution (e.g., concern about the level of pesticides in foodstuffs that leads to wholesale banning of insecticides is unlikely to help the starving). No one wants to hear that cleaning up the environment is going to have a negative impact on them. Public

perception lags behind reality because the reality is sometimes unbearable. In addition to the dwindling oyster population, the current problems with Chesapeake Bay are multifaceted; for example, land subsidence and relative sealevel rise in the Hampton Roads region are ongoing issues. However, HRSD has developed the innovative Sustainable Water Initiative for Tomorrow (SWIFT) program to address many of these issues. Do not associate the acronym SWIFT with the adjectives fast, speedy, rapid, hurried, immediate, or quick. SWIFT is a long-term project, such that installation of the technical equipment and operational procedures have an anticipated completion date of 2030. The SWIFT goal is to inject treated wastewater into the subsurface; specifically, it is designed to inject wastewater treated to drinking water quality into the Potomac Aquifer. Injection of water into the subsurface is expected to raise groundwater pressures, thereby potentially expanding the aquifer system, raising the land surface, and counteracting land subsidence occurring in the Virginia

Coastal Plain. In 2016, construction began on a project at the HRSD Nansemond treatment plant in Suffolk, Virginia, to test injection into the aquifer system. HRSD asked the U.S. Geological Survey to prepare a proposal for installation of an extensometer monitoring station at the test site to monitor groundwater levels and aquifer compaction and expansion. PROBLEM SWIFT is designed to counter land subsidence at various locations in the Hampton Roads area of southern Chesapeake Bay, where land subsidence rates of 1.1 to 4.8 millimeters per year have been observed (Eggleston and Pope, 2013; Holdahl and Morrison, 1974). An obvious indicator of relative sea-level rise in the Hampton Roads region can be seen in Figure 11.4. The dashed lines outline the original 1607 fort palisades at the historic Jamestown Settlement on the James River. As shown, the western section of the original bulwark is completely inundated today; a section of the eastern bulwark is also covered by the James River. A major cause of land subsidence is extensive groundwater pumping, which causes regional aquifer system compaction (Pope and Burbey, 2004). Although aquifer system compaction was measured from the late 1970s to the mid-1990s at two stations in Virginia (Suffolk and Franklin), it has not been measured anywhere in Virginia since 1995. Regular and highly accurate measurements of aquifer compaction are needed to provide information critical for understanding coastal flooding; to protect water resources, natural habitat, and historic sites such as the Jamestown Settlement; and to plan urban and coastal infrastructure in the region. Injection of treated wastewater (treated to drinking water quality) is expected to counteract land subsidence, or raise land surface elevations in the region. Careful monitoring of aquifer system compaction and groundwater levels can be used to optimize the injection process and to improve fundamental understanding of the relation between groundwater pressures and aquifer system compaction and expansion. There is more to HRSD's treated wastewater injection project, SWIFT, than just arresting or mitigating land subsidence and relative sea-level rise in the Hampton Roads region (see Figure 11.5). One of the additional goals of the project is to stop discharge of treated wastewater from seven of its plants, which would mean 18 million pounds a year less of nitrogen, phosphorus, and sediment outfalling into the bay. Assuming SWIFT works as designed this is a huge benefit to Chesapeake Bay in that it may help to prevent or reduce the formation of algae bloom dead zones. Not only would success with the project benefit the bay but it would also be a huge benefit for the ratepayers at HRSD. To meet regulatory guidelines to remove nutrients from discharged treated wastewater would cost millions of dollars and almost non-stop retrofitting at the treatment plants to keep up with advances in treatment technology and regulatory requirements. Another goal of HRSD's SWIFT project is to restore or restock potable groundwater supplies

in the local aquifers. The drawdown of water from the groundwater supply has contributed to land subsidence and a reduction of water available for potable use. The planned restocking of the Hampton Roads groundwater supply with injected wastewater treated to potable water quality is not without its critics, who state that HRSD's wastewater injection project would contaminate potable water aquifers. This is where the so-called "yuck factor" comes into play. The yuck factor, in this particular instance, has to do with the thought that groundwater for consumptive use will be contaminated, basically, with toilet water. This is the common view of many of the critics who feel that HRSD's SWIFT project is nothing more than direct reuse of wastewater; that is, a pipe-to-pipe connection of toilet water to their home water taps. What the critics and others do not realize is that we are already using and drinking treated and recycled toilet water, as was explained earlier in the discussion about an urban water cycle where wastewater is indirectly used. The point is, whether we like it or not, we are using recycled wastewater for potable water use. With regard to the idea that HRSD's SWIFT project would contaminate existing aquifers with toilet water, it is important to point out that this water will be treated (and already is at the York River Treatment Plant) to drinking water quality, with to drinking water quality being key here. A sophisticated and extensive train of unit drinking water quality treatment processes produces treated wastewater that the HRSD general manager and several others have drunk right out of the process, which is discussed in detail later in the text. The bottom line is that the yuck factor involved in drinking treated toilet water is being grossly overstated. WasteWater to Drinking Water Quality Now that HRSD's SWIFT program goals have been described, it is important to return to the focus of this book, drinking water. As pointed out, one of HRSD's main goals is to produce drinking water quality water for human use. How can this be accomplished? How is nasty, polluted, contaminated, flushed, drained wastewater turned into a product that is safe to drink? HRSD uses a treatment train of unit processes that produce quality drinking water. Advanced treatment trains based on reverse osmosis and granular activated carbon were developed for the HRSD groundwater recharge project using the historical WWTP effluent water quality data and the preliminary aquifer recharge water quality goals discussed previously. Three treatment trains were developed from this analysis: (1) reverse osmosis (RO)-based train, (2) nanofiltration (NF)-based train, and (3) granular activated carbon (GAC)-based train (see Figure 11.3). Consideration for each of these treatment trains includes the following:

1. RO-based train—Reverse osmosis is common for potable water reuse projects in California and many international locations (e.g., Singapore, Australia) because of its effective removal of total dissolved solids (TDS), total organic carbon (TOC), and trace organics. California regulations require the use of RO for direct injection reuse projects or a comparable alternative with regulatory approval. RO creates a waste (concentrate) stream that can be difficult and costly to dispose of, especially at inland locations. Most locations where RO has been implemented are located near the ocean where disposal of RO concentrate is convenient and much less costly than at inland locations.
2. NF-based train—Although similar to the RO-based train, the NF-based train operates at significantly lower pressure and generates a less saline concentrate, which results in significant cost savings. This process does not meet California's IPR regulatory requirements but it does provide excellent treatment with significant removal of pathogens and organics. This train offers partial TDS removal by providing a high level of removal of divalent ions (e.g., calcium, magnesium) and moderate re-

removal of monovalent ions (e.g., sodium chloride). NH_3 and $\text{NO}_x\text{-N}$ removal is much lower with NF compared to RO, which results in a lower total nitrogen concentration in the concentrate.

3. **GAC-based train**—This is a modernized version of full-scale operational IPR plants that have operated successfully for decades in Virginia, Texas, and Georgia. GAC adsorption serves as the backbone process for organics removal, and other treatments provide multiple barriers to pathogens and organics. Flocculation and sedimentation remove solids, pathogens, organics, and phosphorus. Ozone provides disinfection of pathogens and oxidation of organics, including oxidation of contaminants of emerging concern and high-molecular-weight organic matter to smaller organic fractions that can be assimilated by biological activity present on GAC media, which is referred to as biological activated carbon (BAC) filtration. This treatment train does not provide any TDS removal and, therefore, does not generate a TDS-enriched waste that might require further treatment prior to discharge.

treatment plant effluent Water Quality HRSD provided historic effluent water quality data for seven WWTPs to identify specific water quality challenges requiring treatment. The WWTPs analyzed include Army Base (AB), Boat Harbor (BH), James River (JR), Nansemond (NP), Virginia Initiative Plant (VIP), and York River (YR) (see Figure 11.5). **Data Sources for Evaluation** The following three primary data sources were used in the evaluation:

- **2013/2014 water quality data**—Detailed water quality data were provided for each WWTP effluent for October 2013 through September 2014. The data were provided as raw data in tables. With few exceptions, these data included the following parameters at the stated frequency: chloride (1x/week), calcium (2x/week), magnesium (2x/week), potassium (2x/week), sodium (2x/week), total alkalinity (3x/week), 5-day biochemical oxygen demand (BOD₅; 5x/week), pH (1x/day), turbidity (1x/day), ammonia-nitrogen ($\text{NH}_3\text{-N}$; 2x/week), $\text{NO}_x\text{-N}$ (4x/week), orthophosphate (3x/week), total Kjeldahl nitrogen (TKN; 4x/week), total phosphorus (TP; 5x/week), and total suspended solids (TSS; 5x/week).
- **2011, 2012, and 2013 water quality data**—Detailed influent and effluent water quality data were provided for each WWTP from the 2011, 2012, and 2013 HRSD wastewater characteristics studies (no James River data were provided for 2013). The data provided were presented as minimum, average, and maximum values. The data included flow (continuous), temperature (3x/day), pH (12x/day), total alkalinity (1x/week), BOD₅ (5x/week), TSS (5x/week), turbidity (5x/week), fecal coliform (5x/week), TKN (frequency not reported), $\text{NO}_x\text{-N}$ (frequency not reported), and TP (frequency not reported). Data were also provided for influent chloride (1x/week) and influent sulfate (4x/week), selected heavy metals (1x/year), and a variety of organics (volatile, base/acid, pesticides, total trihalomethanes [TTHMs]; 1x/year).
- **2014 total dissolved solids data**—Effluent TDS data were provided for each WWTP for January through September 2014. The data were provided as raw data in tables, and data points were provided once per week.

Effluent COD and TOC data collected by HRSD on a weekly basis from February 2015 through April 2015 were also used in the evaluation.

Data Evaluation Evaluation of effluent quality from each of the seven treatment plants involved in the HRSD's SWIFT project included identification of the strength of each data source and was qualitatively documented as excellent, good, or limited. Excellent data included detailed 2013/2014 raw data and minimum, average, and maximum annual data from 2011 through 2013. Good data included a full dataset from only one of the sources. Limited data included data that were only collected once per year. Table

11.3 shows the average WWTP effluent water quality for select parameters and the strength of each data source. In addition, the data in Table 11.3 were analyzed to identify any problematic parameters that would require a specific treatment process or additional treatment to meet probable regulatory requirements or aesthetic issues. Specific challenges revealed in Table 11.3 include the following:

- Total dissolved solids—The drinking water secondary MCL for TDS is 500 mg/L. The average effluent TDS from each WWTP except James River exceeds 500 mg/L; the Army Base plant (1292 mg/L) and Virginia Initiative Plant (853 mg/L) have notably high TDS concentrations.
- Ammonia—Army Base and Boat Harbor plants have an average effluent NH_3 of 25.2 and 16.0 mg-N/L, respectively, although the Army Base plant was recently upgraded to biological nutrient removal (BNR) and now produces effluent with low ammonia and total nitrogen (TN) concentrations that are comparable to HRSD's other biological nutrient removal (BNR) plants. Total nitrogen concentrations in excess of 10 mg/L are typically not allowed for groundwater recharge into potable aquifers; therefore, additional nitrogen treatment would likely be required at the Boat Harbor plant.
- Total trihalomethanes—Elevated TTHM levels were recorded at Nansemond (82.4 $\mu\text{g/L}$) and Williamsburg (64.7 $\mu\text{g/L}$). TTHM levels at the other plants ranged from 3 $\mu\text{g/L}$ to 50 $\mu\text{g/L}$. More TTHM data should be collected as the data sources used were limited. The drinking water primary MCL for TTHMs is 80 $\mu\text{g/L}$.
- Total hardness—Hardness in water is caused by the presence of certain positively charged metallic ions in solution in the water. The most common of these hardness-causing ions are calcium and magnesium; others include iron, strontium, and barium. The two primary constituents of water that determine the hardness of water are calcium and magnesium. If the concentration of these elements in the water is known, the total hardness of the water can be calculated. To make this calculation, the equivalent weights of calcium, magnesium, and calcium carbonate must be known; the equivalent weights are given below: Equivalent weight Calcium (Ca) 20.04 Magnesium (Mg) 12.15 Calcium carbonate (CaCO_3) 50.045 Calcium and magnesium ions are the two constituents that are the primary cause of hardness in water. To find total hardness (mg/L as CaCO_3), we simply add the concentrations of calcium and magnesium ions (mg/L as CaCO_3), using Equation 11.1: Total hardness = Calcium hardness + Magnesium hardness (11.1) When total hardness has been calculated, it is sometimes used to determine another expression of hardness—carbonate and noncarbonate. When hardness is numerically greater than the sum of bicarbonate and carbonate alkalinity, that amount of hardness equivalent to the total alkalinity (both in units of mg/L as CaCO_3) is called the carbonate hardness; the amount of hardness in excess of this is the noncarbonate hardness. When the hardness is numerically equal to or less than the sum of carbonate and noncarbonate alkalinity, all hardness is carbonate hardness and noncarbonate hardness is absent. Again, the total hardness is comprised of carbonate hardness and noncarbonate hardness: Total hardness = Carbonate hardness + Noncarbonate hardness (11.2)

During the evaluation, total hardness data were not specifically provided but were calculated using the detailed calcium and magnesium data. Total hardness in drinking water systems is often limited to 150 mg/L as CaCO_3 or less to avoid customer complaints. The Boat Harbor plant (161 mg/L), Virginia Initiative Plant (181 mg/L), and York River Treatment Plant (194 mg/L) all showed average effluent data above this value. Total hardness concentrations in potable water in the surrounding area were less than the secondary MCL of 500 mg/L.

- Dissolved organic carbon (DOC) and soluble chemical oxygen demand (sCOD)—These are important parameters to measure for potable reuse plants because advanced treatment goals and regulatory requirements are often developed for these constituents. The average DOC and

sCOD concentrations in the effluent from the seven WWTPs ranged from 8.6 to 11.2 mg/L and 25 to 49 mg/L, respectively, values that are within the typical range for WWTPs practicing biological nutrient removal. TOC concentrations above 10 mg/L become increasingly difficult to treat to recommended levels for certain advanced treatment trains so additional DOC sampling and bench and pilot testing are recommended to confirm adequate treatment performance, is ultimately pursued and implemented. In addition to the average WWTP effluent data shown in Table 11.3, selected 99th-percentile effluent data from the 2013/2014 dataset were also analyzed to determine peak loadings from the WWTP that could be problematic for various treatment processes. Peak loadings can be accounted for either by selecting a treatment process that is designed for the maximum values or by providing a large enough equalization volume of primary or secondary effluent to attenuate the loading. Table 11.4 shows the selected parameters of concern based on the 99th-percentile data:

- Nitrate/nitrite-nitrogen—Average effluent NO_x-N levels were well under the nitrate MCL of 10 mg-N/L; however, 99th-percentile data at the Virginia Initiative Plant (10.5 mg/L) and at Williamsburg (0.3 mg/L) show that NO_x-N levels could periodically exceed the nitrate MCL, which could require NO_x-N-specific treatment or additional storage. The 99th-percentile NO_x-N concentration at Boat Harbor was also high, but biological nutrient removal (BNR) is not currently practiced at this plant. When BNR is implemented at Boat Harbor, the variability of the NO_x-N data should be reevaluated.
- Biochemical oxygen demand and total suspended solids—High 99th percentile 5-day biochemical oxygen demand (BOD₅) and TSS levels suggest occasional plant upsets that could be problematic for filtration (granular or membrane). This could require increased storage or treatment or automated monitoring to divert flow away from the AWT plant during high BOD and TSS loadings.
- Total dissolved solids—WWTP effluent TDS values are not expected to fluctuate significantly; yet, Army Base, Virginia Initiative Plant, and Boat Harbor each show 99th-percentile values significantly higher than the average. Periodically high TDS values could violate treatment goals if reverse osmosis is not selected and would require additional storage or provision for divisions.

ADVANCED TREATMENT PRODUCT WATER QUALITY inorganic Water Quality Using the historical water quality data presented previously and the expected performance of each unit process based on professional judgment, mass balance calculations for key inorganic parameters were performed for each treatment train at seven of HRSD's WWTPs. Summary tables for each treatment train are provided in Tables 11.5, 11.6, and 11.7. The detailed mass balance calculations revealed the following:

- The RO-based treatment process provided the lowest concentration of all water quality parameters (Table 11.5); however, treatment to this level may not be necessary in all cases. For example, the finished water TDS concentration was about 50 mg/L, well below the secondary MCL (500 mg/L) and the minimum background TDS in the Potomac Aquifer (~750 mg/L). The very low TDS reverse osmosis permeate may increase mobilization of trace metals in the aquifer, which is undesirable.
- The NF-based treatment process provided excellent water quality, as shown in Table 11.6. The NF process removes very little nitrogen; therefore, the TN concentration in the finished water exceeded the recommended upper range (10 mg/L) at Boat Harbor and approached the 10-mg/L limit at two other WWTPs (VIP and Williamsburg). Nitrification and denitrification improvements at these WWTPs may be necessary to ensure regular compliance with the recommended TN limit. Alternatively, NF membranes that have higher nitrogen removal can be considered; however, their use will result in a higher TDS concentrate stream.
- The GAC-based treatment process provided excellent water quality, as shown in Table 11.7. Specific

considerations related to this process include the following:

- Although some incidental nitrification may occur in the biological activated carbon filters, the process is not intended nor typically designed to remove nitrogen. Therefore, nitrogen removal should be considered at the upstream WWTPs, where nitrification and denitrification improvements would be necessary to ensure regular compliance with the recommended TN limit.
- No TDS are removed through this process. The Army Base and VIP plants showed elevated TDS levels that regularly exceeded 750 mg/L. Upstream mitigation, such as reducing infiltration and inflow in areas with high TDS or eliminated industrial discharge high in TDS, may be required at these locations if a TDS limit of 750 mg/L is established.
- Hardness removal with chemical precipitation may be required at three plants (Boat Harbor, VIP, and York River), although more investigation is necessary to determine whether or not the total hardness (161 to 194 mg/L as CaCO₃) at these plants is acceptable from aesthetic and aquifer geochemistry perspectives. If not, the proposed flocculation–sedimentation process shown for the GAC-based treatment train could be modified to a chemical softening process for those plants with elevated hardness.

organic Water Quality Bulk Organics The application of robust treatment barriers for the removal of organics has historically been a central tenet of implementing full-scale potable reuse projects to address the presence of unknown organic compounds of chronic health concern that may be present in the secondary effluent—a significant and pressing example of the old “we do not know what we do not know” syndrome. As presented in Table 11.8, regulations and permits for potable reuse projects have been developed by establishing limits on bulk organic parameters, such as COD and TOC, which act as surrogates for organic compounds of wastewater origin. Virginia established a COD limit of 10 mg/L for the Occoquan and Dulles area watershed policies, which apply to the Upper Occoquan Sewage Authority (UOSA) IPR project (constructed in 1978) and the Broad Run Water Reclamation Facility (BRWRF) (constructed in 2008), respectively. California and Florida have established TOC limits of 0.5 mg/L and 3 mg/L, respectively, in their IPR regulations. An advanced water treatment plant’s finished water COD and TOC concentration that would need to comply with the established permit limit is dependent on the initial concentration in the WWTP effluent and the specific treatment processes employed at the advanced water treatment plant. Table 11.9 shows the estimated finished water TOC concentrations from the three proposed advanced water treatment plant treatment trains (i.e., RO, NA, and BAC) when treating effluent from each of HRSD’s WWTPs. The calculations use full-scale advanced water treatment plant effluent TOC and DOC sampling and treatment process pilot testing. The following can be concluded from the information in the table:

- Compliance with a California-based TOC limit of 0.5 mg/L could only be achieved by implementing an RO-based treatment train.
- Compliance with a Florida-based UOSA-type permit (3 mg/L TOC and 10 mg/L COD) could likely be achieved at most WWTPs by any of the three proposed treatment trains or by a hybrid treatment train that combined partial RO treatment with GAC-based treatment.
- GAC-based advanced water treatment plants will require regular replacement or regeneration of the GAC media for consistent TOC removal. Pilot testing is necessary to determine the GAC regeneration frequency requirements.
- Measurement on a regular basis of TOC and DOC in the final effluent from each WWTP is recommended to accurately determine TOC removal requirements.

Trace Organics Earlier, contaminants of emerging concern (CECs) were mentioned. Additional concerns about CECs continue to be expressed with regard to the potential for chronic human health effects related to the thousands of organic chemicals that may end up in wastewater effluent at trace levels (mg/L). Fur-

thermore, the efficacy of conventional water treatment processes that may end up treating source waters that have some effluent contribution is typically low. Each advanced treatment process considered in this discussion differs in its effectiveness at removing CECs. Research has shown that RO-based, NF-based, and GAC-based potable reuse treatment trains provide multiple unit processes that are effective barriers to a wide range of CECs. The RO and NF-based treatment trains provide substantial removal through membranes (RO/NF) and ultraviolet advanced oxidation process (UVAOP), while the GAC-based treatment train provides significant removal through ozone–biological activated carbon (BAC) and granular activated carbon (GAC). Table 11.10 shows representative removals by advanced treatment processes for a variety of CECs as determined through recent research and monitoring of full-scale treatment facilities. These processes are redundant in the removal of some CECs (i.e., provide multiple barriers to their passage) and are complementary in the removal of others. For example, both ozone and GAC are effective barriers to the anticonvulsant drug carbamazepine, but only GAC acts as an effective barrier to the flame-retardant TCEP. No one process provides complete removal of all compounds, but RO generally provides the best removal of a wide range of compounds. However, these compounds are not destroyed or transformed by RO but instead are transferred to the RO concentrate (at a higher concentration); thus, their presence in the concentrate must be considered, particularly when the concentrate is discharged to a receiving water body. At the present time, treatment for all CECs does not appear to be a differentiator among potable reuse treatment trains. Although health effects of many CECs—either alone or as mixtures—have not been demonstrated at the ng/L concentrations typically detected in wastewater effluent, the proposed treatment trains do reduce the concentrations of many of these chemicals to a significant degree. Meanwhile, the USEPA is prioritizing and studying a number of chemicals through their candidate contaminant list program.

RO CONCENTRATE DISPOSAL* To this point in the book we have discussed the benefits of reverse osmosis operating systems. It is important to point out, however, that along with the good there is the not so good; that is, RO systems have their advantages but they also have a few disadvantages. The one disadvantage pointed out and discussed here is the major one—that is, concentrate disposal. Where is the concentrated wastestream to be disposed of?

mass balance principle To gain a better understanding of membrane disposal issues and techniques we begin with a discussion of mass balance. The simplest way to express the fundamental engineering principle of mass balance is to say, “Everything has to go somewhere.” More precisely, the law of conservation of mass says that when chemical reactions take place matter is neither created nor destroyed. What this important concept allows us to do is track materials (concentrates)—that is, pollutants, microorganisms, chemicals, and other materials—from one place to another. The concept of mass balance plays an important role in reverse osmosis system operations (especially in desalinization) where we assume a balance exists between the material entering and leaving the RO system: “What comes in must equal what goes out.” The concept is very helpful for evaluating biological systems and developing sampling and testing procedures, as well as many other unit processes within any treatment or processing system. All desalinization processes have two outgoing process streams: (1) the product water, which is lower in salt than the feed water, and (2) a concentrated stream that contains the salts removed from the product water. Even distillation has a “bottoms” solution that contains salt from the vaporized water. The nature of the concentrate stream depends on the salinity of the feed water, the amount of product water recovered, and the

purity of the product water. To determine the volume and concentration of the two outgoing streams, a mass balance is constructed. It is necessary to know the recovery rate of water, the rejection rate of salt, and the input flow and concentration to solve equations for the flow and concentration of the product and concentrate.

Reverse osmosis concentrate Disposal practices Reverse osmosis concentrate is disposed of by several methods, including surface water discharge, sewer discharge, deep well injection, evaporation ponds, spray irrigation, and zero liquid discharge.

Surface Water and Sewer Disposal Disposal of concentrate to surface water and sewers are the two most widely used disposal options for both desalting membrane processes. Post-1992 data provide the following statistics:

Disposal Option	Percent of Desalting Plants
Surface water disposal	45%
Disposal to sewer	42%
Total	87%

This disposal option, although not always available, is the simplest option in terms of equipment involved and is frequently the lowest cost option. As will be seen, however, the design of an outfall structure for surface water disposal can be complex. Disposal to surface water involves conveyance of the concentrate or backwash to the site of disposal and an outfall structure that typically involves a diffuser and outlet ports or valve mounted on the diffuser pipe. Factors involved in the outfall design are discussed in this section, and cost factors are presented. However, due to the large number of cost factors and the large variability in design conditions associated with surface water disposal, a relatively simple cost model cannot be developed. Disposal to surface waters requires a National Pollutant Discharge Elimination System (NPDES) permit. Disposal to the sewer involves conveyance to the sewer site and typically a negotiated fee to be paid to the WWTP. Because the negotiated fees can range from zero to substantial, there is no model that can be presented. No disposal permits are required for this disposal option. Disposal of concentrate or backwash to the sewer, however, affects WWTP effluent that requires an NPDES permit. With regard to design considerations for disposal to surface water, a brief discussion of ambient conditions, discharge conditions, regulations, and the outfall structure is provided below. Because receiving waters can include rivers, lakes, estuaries, canals, oceans, and other bodies of water, the range of ambient conditions can vary greatly. Ambient conditions include the geometry of the receiving water bottom and the receiving water salinity, density, and velocity. Receiving water salinity, density, and velocity may vary with water depth, distance from the discharge point, and time of day and year. Discharge conditions include the discharge geometry and the discharge flow conditions. The discharge geometry can vary from the end of the pipe to a lengthy multiple-port diffuser. The discharge can be at the water surface or submerged. The submerged outfall can be buried (except for ports) or not. Much of the historical outfall design work deals with discharges from WWTPs. These discharges can be very large—up to several hundred million gallons per day in flow. In ocean outfalls and in many inland outfalls, these discharges are of lower salinity than the receiving water, and the discharge has positive buoyancy. The less dense effluent rises in the more dense receiving water after it is discharged. The volume of flow of membrane concentrates is on the lower side of the range of WWTP effluent volumes, extending up to perhaps 15 MGD. Membrane concentrate, as opposed to WWTP effluent, tends to be of higher salinity than most receiving waters, resulting in a condition of negative buoyancy where the effluent sinks after it is discharged. This raises concerns about the potential impact of the concentrate on the benthic community at the receiving water bottom. Any possible effect on the benthic community

is a function of the local ecosystem, the composition of the discharge, and the degree of dilution present at the point of contact. The chance of an adverse impact is reduced by increasing the amount of dilution at the point of bottom contact through diffuser design. With regard to concentrate discharge regulations it is important to note that receiving waters can differ substantially in their volume, flow, depth, temperature, composition, and degree of variability in these parameters. The effect of discharge of a concentrate or backwash to a receiving water can vary widely depending on these factors. The regulation of effluent disposal to receiving waters involves several considerations, including the end-of-pipe characteristics of the concentrate or backwash. Comparison is made between receiving water quality standards (dependent on the classification of the receiving water) and the water quality of the effluent to determine disposal feasibility. In addition, in states such as Florida, the effluent must also pass tests where test species, chosen based on the receiving water characteristics, are exposed to various dilutions of the effluent. Because the nature of the concentrate or backwash is different than that of the receiving water, there is a region near the discharge area where mixing and subsequent dilution of the concentrate or backwash occurs. Where conditions cannot be met at the end of the discharge pipe, a mixing zone may be granted by the regulatory agency. The mixing zone is an administrative construct that defines a limited area or volume of the receiving water where this initial dilution of the discharge is allowed to occur. The definition of an allowable mixing zone is based on receiving water modeling. The regulations require that certain conditions be met at the edge of the mixing zone in terms of concentration and toxicity.

When the mixing zone conditions have been met, the outfall structure can be properly designed and installed. Actually, the purpose of the outfall structure is to ensure that mixing conditions can be met and that discharge of the effluent, in general, will not produce any damaging effect on the receiving water, its lifeforms, wildlife, and the surrounding area. In a highly turbulent and moving receiving water with large volume relative to the effluent discharge, simple discharge from the end of a pipe may be sufficient to ensure rapid dilution and mixing of the effluent. For most situations, however, the mixing can be improved substantially through the use of a carefully designed outfall structure. Such a design may be necessary to meet regulatory constraints. The most typical outfall structure for this purpose consists of a pipe of limited length mounted perpendicular to the end of the delivery pipe. This pipe, called a diffuser, has one or more discharge ports along its length.

Disposal to the Sewer Where possible, this means of disposal is simple and usually cost effective. Disposal to a sewer does not require a permit but does require permission from the wastewater treatment plant.

The impact of both the flow volume and composition of the concentrate will be considered by the WWTP, as it will affect their capacity buffer and their NPDES permit. The high volume of some concentrates prohibits their discharge to the local WWTP. In other cases, concerns are focused on the increased TDS level of the WWTP effluent that results from the concentrate discharge. The possibility of disposal to a sewer is highly site dependent. In addition to the factors mentioned, the possibility is influenced by the distance between the two facilities, by whether the two facilities are owned by the same entity, and by future capacity increases anticipated. Where disposal to a sewer is allowed, the WWTP may be required to pay fees based on volume or composition.

pathogen removal Various states have developed different approaches to regulating pathogen removal by indirect potable reuse plants. For example, Virginia permitted the UOSA indirect potable reuse plant and the Broad Run Water Reclamation Facility based on achieving a nondetect concentration of *Escherichia*

coli (less than 2 cfu/100 mL). Other states have taken a different approach. For example, California requires 12-log reduction of viruses and 10-log reduction of *Cryptosporidium* and *Giardia* from the raw wastewater to the advanced water treatment plant finished water. Pathogen removal by each of the three proposed treatment trains is significant and would result in nondetect concentrations for all indicator organisms typically used in wastewater treatment (e.g., *E. coli*, total coliform, fecal coliform) assuming proper operation. Therefore, compliance with a UOSA-type permit or Florida's pathogen-related indirect potable reuse regulations would be met by all three proposed treatment trains. Compliance with the California regulations may be more challenging, especially for GAC-based treatment, because of the high log reduction requirements. Tables 11.11 and 11.12 show the calculated log reduction credits for each of the proposed treatment trains. Note that log reduction credits associated with 6 months of subsurface travel time as water moves through the aquifer (soil aquifer treatment) have been assumed in the calculations. Discussion with the Virginia regulators is necessary to determine how the proposed HRSD groundwater recharge project would be regulated with respect to pathogen removal.

Disinfection byproducts Excessive formation of trihalomethanes (THMs) at WWTPs is fairly common, especially for plants that provide good nitrification. Low effluent NH_3 concentrations at these plants lead to the formation of free chlorine (rather than chloramines) during chlorine disinfection, which, when reacted with bulk organics, has a propensity to form high levels of THMs. N-nitrosodimethylamine (NDMA), another disinfection byproduct, can also form in significant concentrations during the disinfection process at WWTPs depending on the precursors in the water and the type of chlorination practiced. Little NDMA forms in the presence of free chlorine, but significant concentrations typically form in the presence of chloramines, with dichloramine resulting in more rapid formation kinetics than monochloramine. Both THMs and NDMA can be removed by advanced water treatment processes through specialized design, but a more cost-efficient approach is to prevent their formation by withdrawing the water from the WWTP prior to disinfection (upstream of the chlorine contact basin). Specific withdrawal points at each WWTP and the potential treatment required for THMs and NDMA removal should be considered in the next stage of this project.

ANTICIPATED IMPROVEMENTS TO HRSD'S EXISTING WWTPS Some operational and capital improvements to the existing WWTPs may be required depending on the AWT train selected for implementation and the final effluent water quality produced at each WWTP. Table 11.13 shows the improvements that will likely be required. Analysis regarding WWTP improvements should be ongoing.

THE BOTTOM LINE All of these processes—preliminary screening, filtration, disinfection, and the advanced processes necessary for specialized water problems—are in place to serve one primary, essential purpose: to supply the consumer with safe potable water. The consumer may put this water to a wide variety of uses, from drinking it to using it to water the lawn, but those uses are in many ways beside the point, as safe potable water is essential for human life. From the information presented to this point, it is obvious that the bottom line is that any of the three advanced water treatment (AWT) trains—RO-based, NF-based, or GAC-based—is likely to be viable for groundwater recharge by effluent generated from HRSD's WWTPs. Finished water quality produced by each train will be excellent with respect to pathogen and organics removal, but use of the RO-based or NF-based treatment train is necessary if TDS reduction is required. Partial RO or NF treatment could be used depending on the degree of TDS reduction required. BNR improvements will be required at some of the WWTPs to reduce the TN concentra-

tion and the propensity for organic fouling membranes in the RO and NF-based trains.

Selection of the advanced water treatment train to be implemented at each WWTP should be based on numerous factors, such as finished water quality, wastewater discharge requirements, operability, sustainability, site-specific characteristics (e.g., space, existing infrastructure, hydraulics), and capital and operating costs. Ultimate selection of the advanced water treatment train will also be dictated by regulatory requirements related to treatment, finished water quality, and wastewater discharge requirements that have not yet been established; therefore, engaging the appropriate regulatory agencies is important during the next phase of this project. Treatment selection may also be influenced by public perception. Because HRSD's SWIFT project is a work in progress, with time for adjustment here, there, and almost anywhere, other action items that will influence advanced water treatment train selection should be considered, including the following:

- Regularly sample at each WWTP for COD, sCOD, TOC, DOC, all contaminants regulated by primary MCLs, selected CECs, and parameters specific to the design of RO and NF treatment (e.g., barium, strontium, fluoride, silica, alkalinity, pH).
- Regularly measure water quality (e.g., pH, alkalinity, TDS, hardness) in numerous Potomac Aquifer product wells.
- Evaluate site-specific conditions at each WWTP that may influence AWT train selection, including site space, hydraulics, geotechnical conditions, electrical service, and use of existing infrastructure for AWT.
- Conduct an industrial and commercial water quality discharge study to characterize risk and to identify chemicals of concern that may be discharged to the collection system.
- Determine potential causes for high TDS concentrations at WWTPs where effluent TDS is greater than 500 mg/L.

Upgrading Security Worldwide conflicts are ongoing and seem never ending. One of the most important conflicts of our time, including the ongoing Israeli–Palestinian conflict, is in fact conflict over scarce but vital water resources. This conflict over water, unfortunately, may be a harbinger of things to come.

INTRODUCTION* Each of the public water systems (PWSs) in the United States regularly supplies drinking water to at least 25 persons or 15 service connections. Of the total U.S. population, 90% is served by PWSs, while the remainder is served primarily by private wells. PWSs are divided into community water systems (CWSs) and noncommunity water systems (NCWSs). Examples of CWSs include municipal water systems that serve mobile home parks or residential developments, and examples of NCWSs include schools, factories, churches, commercial campgrounds, hotels, and restaurants (USEPA, 2017). Because drinking water is consumed directly, health effects associated with contamination have long been major concerns. In addition, interruption or cessation of the drinking water supply can disrupt society, impacting human health and critical activities such as fire protection. Although they may have no clue as to its true economic value and to its future worth, the general public correctly perceives drinking water as being central to the life of an individual and of society. Federal and state agencies have long been active in addressing these risks and threats to water utilities through regulations, technical assistance, research, and outreach programs. As a result, an extensive system of regulations governing maximum contaminant levels of 90 conventional contaminants (most established by the U.S. Environmental Protection Agency), construction and operating standards (implemented mostly by the states), monitoring, emergency response planning, training, research, and education have been developed to better protect the nation's drinking water supply and receiving waters. Since the events of 9/11, the U.S. Environmental Protection Agency (USEPA) has been designated as the sector-specific agency responsible for infrastructure protection activ-

ities for the nation's drinking water system. The USEPA is utilizing its position within the water sector and working with its stakeholders to provide information to help protect the nation's drinking water supply from terrorism or other intentional acts.

CONSEQUENCES OF 9/11 One consequence of the events of September 11 was the USEPA's directive to establish a Water Protection Task Force to ensure that activities to protect and secure the country's water supply and wastewater treatment infrastructure are comprehensive and carried out expeditiously. Another consequence is a heightened concern among citizens in the United States over the security of their critical water infrastructure. The nation's water infrastructure, consisting of several thousand publicly owned water treatment works, more than 100,000 pumping stations, and hundreds of thousands of miles of water distribution lines, is one of America's most valuable resources. This country's water treatment and distribution/collection systems are valued at more than \$2.5 trillion. Almost immediately after 9/11, then-Governor Tom Ridge (Henry, 2002) pointed out the security role for public professionals:

Americans should find comfort in knowing that millions of their fellow citizens are working every day to ensure our security at every level—federal, state, county, municipal. These are dedicated professionals who are good at what they do. I've seen it up close, as Governor of Pennsylvania . . . but there may be gaps in the system. The job of the Office of Homeland Security will be to identify those gaps and work to close them.

Eliminating these gaps in the system has driven many water and wastewater facilities to increase their security. Moreover, the USEPA made several recommendations to increase security and reduce threats from terrorism (USEPA, 2001). The recommendations include the following:

1. Guard against unplanned physical intrusion (water/wastewater).
1. Lock all doors and set alarms at your office, pumping stations, treatment plants, and vaults, and make it a rule that doors are locked and alarms are set.
2. Limit access to facilities and control access to pumping stations and chemical and fuel storage areas, giving close scrutiny to visitors and contractors.
3. Post guards at treatment plants, and post "Employee Only" signs in all restricted areas.
4. Control access to storm sewers.
5. Secure hatches, metering vaults, manholes, and other access points to the sanitary collection system.
6. Increase lighting in parking lots, treatment bays, and other areas with limited staffing.
7. Control access to computer networks and control systems, and change the passwords frequently.
8. Do not leave keys in equipment or vehicles at any time.
1. Make security a priority for employees.
1. Conduct background security checks on employees at hiring and periodically thereafter.
2. Develop a security program with written plans and train employees frequently.

3. Be sure that all employees are aware of communications protocols with relevant law enforcement, public health, environmental protection, and emergency response organizations.
 4. Be sure that employees are fully aware of the importance of vigilance and the seriousness of breaches in security; make note of unaccompanied strangers on the site, and immediately notify designated security officers or local law enforcement agencies.
 5. Consider varying the timing of operational procedures, if possible, so someone watching will realize that the pattern changes.
 6. Upon the dismissal of an employee, change passcodes and make sure keys and access cards are returned.
 7. Provide customer service staff with training and checklists of how to handle a threat if it is called in.
1. Coordinate actions for an effective emergency response.
 1. Review existing emergency response plans, and ensure they are current and relevant.
 2. Make sure employees have necessary training in emergency operating procedures.
 3. Develop clear protocols and chains of command for reporting and responding to threats with relevant emergency, law enforcement, environmental, public health officials, consumers, and the media. Practice the emergency protocols regularly.
 4. Be sure that key utility personnel (both on and off duty) have access to crucial telephone numbers and contact information at all times. Keep the call list up to date.
 5. Develop close relationships with local law enforcement agencies, and make sure they know where critical assets are located. Request they add your facilities to their routine rounds.
 6. Work with local industries to ensure that their pretreatment facilities are secure.
1. Invest in security and infrastructure improvements.
 1. Assess the vulnerability of distribution systems, major pumping stations, water treatment plants, chemical and fuel storage areas, outfall pipes, and other key infrastructure elements.
 2. Assess the vulnerability of the stormwater collection system. Determine where large pipes run near or beneath government buildings, banks, commercial districts, or industrial facilities or are contiguous with major communication and transportation networks.
 3. Move as quickly as possible to make the most obvious and cost-effective physical improvements, such as perimeter fences, security lighting, tamperproof manhole covers and valve boxes, etc.
 4. Improve computer system and remote operational security.
 5. Use local citizen watches.
 6. Seek financing to implement more expensive and comprehensive system improvements

Ideally, in a perfect world, water infrastructure would be secured in a layered fashion (i.e., the multiple barrier approach). Layered security systems are vital. Utilizing the protection-in-depth approach, which requires that adversaries defeat several protective barriers or security layers to accomplish their goal, water infrastructure can be made more secure. Protection in depth is a term commonly used by the military to describe security measures that reinforce one another and mask the defense mechanisms from view of intruders, thus allowing the defender time to respond to intrusion or attack. A prime example of the use of the multiple-barrier approach to ensure security and safety is demonstrated by the practices of the bottled water industry. In the aftermath of 9/11 and the increased emphasis on homeland security, a shifted paradigm of national security and vulnerability awareness has emerged. Recall that in the immediate aftermath of the 9/11 tragedies, emergency responders and others responded quickly and worked to exhaustion. In addition to the emergency responders, bottled water companies responded immediately by donating several million bottles of water to the crews at the crash sites in New York, at the Pentagon, and in Pennsylvania. The International Bottled Water Association reported that “within hours of the first attack, bottled water was delivered where it mattered most: to emergency personnel on the scene who required ample water to stay hydrated as they worked to rescue victims and clean up debris” (IBWA, 2004). Bottled water companies continued to provide bottled water to responders and rescuers at the 9/11 sites for the duration. These patriotic actions by the bottled water companies, however, beg the question: How do we ensure the safety and security of the bottled water provided to anyone? IBWA’s answer is to use a multiple-barrier approach, along with other defense principles, to enhance the safety and security of bottled water. IBWA (2004) described its multiple-barrier approach as follows:

A multiple-barrier approach—Bottled water products are produced utilizing a multiple-barrier approach, from source to finished product, that helps prevent possible harmful contaminants (physical, chemical or microbiological) from adulterating the finished product as well as storage, production, and transportation equipment. Measures in a multiple-barrier approach may include source protection, source monitoring, reverse osmosis, distillation, filtration, ozonation or ultraviolet (UV) light. Many of the steps in a multibarrier system may be effective in safeguarding bottled water from microbiological and other contamination. Piping in and out of plants, as well as storage silos and water tankers are also protected and maintained through sanitation procedures. In addition, bottled water products are bottled in a controlled, sanitary environment to prevent contamination during the filling operation. In water infrastructure security, protection in depth is used to describe a layered security approach. A protection-in-depth strategy uses several forms of security techniques and devices against an intruder and does not rely on a single defensive mechanism to protect infrastructure. By implementing multiple layers of security, a hole or flaw in one layer is covered by the other layers, and an intruder will have to break through each layer without being detected. This layered approach implies that no matter how they attempt to accomplish their goal, intruders will encounter effective elements of the physical protection system. In the following sections, various security hardware and devices are described. These devices serve the main purpose of providing security against physical or digital intrusion; that is, they are designed to delay and deny intrusion and are normally coupled with detection and assessment technology. Keep in mind, however, that when it comes to trying to make something absolutely secure from intrusion or attack there is no absolute silver bullet.

SECURITY HARDWARE AND DEVICES Water infrastructure security devices or products can be grouped into four general categories (USEPA, 2005):

- Physical asset monitoring and control devices • Water monitoring devices • Communication/integration
- Cyber protection devices

physical asset monitoring and control devices Aboveground Outdoor Equipment Enclosures Water and wastewater systems consist of multiple components spread over a wide area and typically include a centralized treatment plant, as well as distribution or collection system components that are usually distributed at multiple locations throughout the community. In recent years, however, distribution and collection system designers have favored placing critical equipment—especially assets that require regular use and maintenance—above ground. A primary reason for doing so is that locating this equipment above ground eliminates the safety risks associated with confined space entry, which is often required for the maintenance of equipment located below ground. In addition, space restrictions often limit the amount of equipment that can be located inside, and there are concerns that some types of equipment (such as backflow-prevention devices) can, under certain circumstances, discharge water that could flood pits, vaults, or equipment rooms; therefore, many pieces of critical equipment are located outdoors and above ground. Examples of the many different system components that can be installed outdoors and above ground include

- Backflow-prevention devices • Air release and control valves • Pressure vacuum breakers • Pumps and motors • Chemical storage and feed equipment • Meters • Sampling equipment • Instrumentation

Much of this equipment is installed in remote locations or in areas where the public can access it. One of the most effective security measures for protecting aboveground equipment is to place it inside a building. Where this is not possible, enclosing the equipment or parts of the equipment using some sort of commercial or homemade add-on structure may help to prevent tampering with the equipment. Equipment enclosures can generally be categorized into one of four main configurations:

- One-piece, drop-over enclosures • Hinged or removable-top enclosures • Sectional enclosures • Shelters with access locks

Other security features that can be implemented on aboveground, outdoor equipment enclosures include locks, mounting brackets, tamper-resistant doors, and exterior lighting.

Active Security Barriers (Crash Barriers) Active security barriers (or crash barriers) are large structures that are placed in roadways at entrance and exit points of protected facilities to control vehicle access to these areas. These barriers are placed perpendicular to traffic to block the roadway, and traffic can only pass the barrier if it is moved out of the roadway. These types of barriers are typically constructed from sturdy materials, such as concrete or steel, so vehicles cannot penetrate them. They are also situated at such a height off the roadway that vehicles cannot go over or under them. The key difference between active security barriers, which include wedges, crash beams, gates, retractable bollards, and portable barricades, and passive security barriers, which include immovable bollards, jersey barriers, and planters, is that active security barriers are designed so they can be easily raised and lowered or moved out of the roadway to allow authorized vehicles to pass them. Many of these types of barriers are designed so they can be opened and closed automatically (i.e., mechanized gates, hydraulic wedge barriers), while others are easy to open and close manually (swing crash beams, manual gates). In contrast to active barriers, passive barriers are permanent, immovable barriers that are typically used to protect the perimeter of a protected facility, such as sidewalks and other areas that do not require vehicular traffic to pass them. Several of the major types of active security barriers such as wedge barriers, crash beams, gates, bollards, and

portable/removable barricades are described below. Wedge barriers are plated, rectangular steel buttresses approximately 2 to 3 feet high that can be raised and lowered from the roadway. When they are in the open position, they are flush with the roadway, and vehicles can pass over them; however, when they are in the closed (armed) position, they project up from the road at a 45° angle, with the upper end pointing toward the oncoming vehicle and the base of the barrier away from the vehicle. Generally, wedge barriers are constructed from heavy-gauge steel or concrete that contains an impact-dampening iron rebar core that is resistant to breaking or cracking, thereby allowing the barrier to withstand the impact of a vehicle attempting to crash through it. In addition, both of these materials help to transfer the energy of the impact over the entire volume of the barrier, thus helping to prevent the barrier from being sheared off its base. Also, because of the angle of the barrier, the force of any vehicle impacting the barrier is distributed over the entire surface of the barrier and is not concentrated at the base, which helps prevent the barrier from breaking off at the base. Finally, any vehicles attempting to drive over the barrier will most likely be hung up on it. Wedge barriers can be fixed or portable. Fixed wedge barriers can be mounted on the surface of the roadway (surface-mounted wedges) or in a shallow mount in the road's surface, or they can be installed completely below the road surface. Surfacemounted wedge barricades operate by rising from a flat position on the surface of the roadway, whereas shallow-mount wedge barriers rise from their resting position just below the road surface. In contrast, below-surface wedge barriers operate by rising from beneath the road surface. Both the shallow-mounted and surface-mounted barriers require little or no excavation and thus do not interfere with buried utilities. These types of barriers project above the road surface and block traffic when they are raised into the armed position. When they are disarmed and lowered, they are flush with the road, thereby allowing traffic to pass. Portable wedge barriers are moved into place on wheels that are removed after the barrier has been set into place. Installing rising wedge barriers requires preparation of the road surface. Installing surface-mounted wedges does not require that the road be excavated; however, the road surface must be intact and strong enough to allow the bolts anchoring the wedge to the road surface to attach properly. Shallow-mount and below-surface wedge barricades require excavation of a pit that is large enough to accommodate the wedge structure, as well as any arming/disarming mechanisms. Generally, the bottom of the excavation pit is lined with gravel to allow for drainage. A gravity drain or selfpriming pump can be installed in areas not sheltered from rain or surface runoff. Crash beam barriers consist of aluminum beams that can be opened or closed across the roadway. Although crash beam designs vary, every crash beam system consists of an aluminum beam that is supported on each side by a solid footing or buttress, which is typically constructed from concrete, steel, or some other strong material. Beams typically contain an interior steel cable (at least 1 inch in diameter) to give the beam added strength and rigidity. The beam is connected by a heavy-duty hinge or other mechanism to one of the footings so it can swing or rotate out of the roadway when it is open and can swing back across the road when it is in the closed (armed) position, blocking the road and inhibiting access by unauthorized vehicles. The non-hinged end of the beam can be locked into its footing, thus providing anchoring for the beam on both sides of the road and increasing the resistance of the beam to vehicles attempting to penetrate through it. In addition, if the crash beam is hit by a vehicle, the aluminum beam transfers the impact energy to the interior cable, which in turn transfers the impact energy through the footings and into their foundation, thereby minimizing the chance that the impact will snap the beam and allow the intruding vehicle to pass through. Crash beam barriers can employ drop-arm, cantilever,

or swing beam designs. Drop-arm crash beams operate by raising and lowering the beam vertically across the road. Cantilever crash beams are projecting structures that are opened and closed by extending the beam from the hinge buttress to the receiving buttress located on the opposite side of the road. In the swing beam design, the beam is hinged to the buttress such that it swings horizontally across the road. Generally, swing beam and cantilever designs are used at locations where a vertical lift beam is impractical; for example, the swing beam or cantilever designs are utilized at entrances and exits with overhangs, trees, or buildings that would physically block the operation of the drop-arm beam design. Installing any of these crash beam barriers involves the excavation of a pit approximately 48 inches deep for both the hinge and the receiver footings. Due to the depth of excavation, the site should be inspected for underground utilities before digging begins. In contrast to wedge barriers and crash beams, which are typically installed separately from a fence line, gates are often integrated units of a perimeter fence or wall around a facility. Gates are basically movable pieces of fencing that can be opened and closed across a road. When the gate is in the closed (armed) position, the leaves of the gate lock into steel buttresses that are embedded in a concrete foundation located on both sides of the roadway, thereby blocking access to the roadway. Generally, gate barricades are constructed from a combination of heavy-gauge steel and aluminum that can absorb an impact from vehicles attempting to ram through them. Any remaining impact energy not absorbed by the gate material is transferred to the steel buttresses and their concrete foundation. Gates can utilize a cantilever, linear, or swing design. Cantilever gates are projecting structures that operate by extending the gate from the hinge footing across the roadway to the receiver footing. A linear gate is designed to slide across the road on tracks via a rack-and-pinion drive mechanism. Swing gates are hinged so they can swing horizontally across the road. Installation of the cantilever, linear, or swing gate designs involves the excavation of a pit approximately 48 inches deep for both the hinge and receiver footings to which the gates are attached. Again, due to the depth of excavation, the site should be inspected for underground utilities before digging begins. Bollards are vertical barriers at least 3 feet tall and 1 to 2 feet in diameter that are typically set 4 to 5 feet apart from each other so they block vehicles from passing between them. Bollards can be fixed in place, removable, or retractable. Fixed and removable bollards are passive barriers that are typically used along building perimeters or on sidewalks to prevent vehicle access while still allowing pedestrians to pass through them. In contrast to passive bollards, retractable bollards are active security barriers that can easily be raised and lowered to allow vehicles to pass between them; thus, they can be used in driveways or on roads to control vehicular access. When the bollards are raised, they project above the road surface and block the roadway; when they are lowered, they sit flush with the road surface and allow traffic to pass over them. Retractable bollards are typically constructed from steel or other materials that have a low weight-to-volume ratio so they require low power to raise and lower. Steel is also more resistant to breaking than is a more brittle material such as concrete, and it is better able to withstand direct vehicular impact without breaking apart. Retractable bollards are installed in a trench dug across a roadway, typically at an entrance or a gate. Installing retractable bollards requires preparing the road surface. Depending on the vendor, bollards can be installed either in a continuous slab of concrete or in individual excavations with concrete poured in place. The required excavation for a bollard is typically slightly wider and slightly deeper than the bollard height when it is extended above ground. The bottom of the excavation is typically lined with gravel to allow drainage. The bollards are then connected to a control panel that controls the raising and lowering of the bollards. Installation

typically requires mechanical, electrical, and concrete work; if utility personnel with these skills are available, then the utility can install the bollards themselves. Portable or removable barricades, which can include removable crash beams and wedge barriers, are mobile obstacles that can be moved in and out of position on a roadway; for example, a crash beam may be completely removed and stored off-site when it is not needed. An additional example would be wedge barriers that are equipped with wheels that can be removed after the barricade is towed into place. When portable barricades are needed, they can be moved into position rapidly. To provide them with added strength and stability, they are typically anchored to buttress boxes that are located on either side of the road. These buttress boxes, which may or may not be permanent, are usually filled with sand, water, cement, gravel, or concrete to make them heavy and aid in stabilizing the portable barrier. In addition, these buttresses can help dissipate any impact energy from vehicles crashing into the barrier itself. Because these barriers are not anchored into the roadway, they do not require excavation or other related construction for installation, and they can be assembled and made operational in a short period of time. The primary shortcoming to this type of design is that these barriers may move if they are hit by vehicles; therefore, it is important to carefully assess the placement and anchoring of these types of barriers to ensure that they can withstand the types of impacts that may be anticipated at that location. Because the primary threat to active security barriers is that vehicles will attempt to crash through them, their most important attributes are their size, strength, and crash resistance. Other important features for an active security barrier are the mechanisms by which the barrier is raised and lowered to allow authorized vehicle entry, as well as such other factors as weather resistance and safety features.

Alarm Systems An alarm system is a type of electronic monitoring system that is used to detect and respond to specific types of events, such as unauthorized access to an asset, or a possible fire. In water and wastewater systems, alarms are also used to alert operators when process operating or monitoring conditions go out of preset parameters (i.e., process alarms). These types of alarms are primarily integrated with process monitoring and reporting systems (e.g., SCADA systems). Note that this discussion does not focus on alarm systems that are not related to the processes of a utility. Alarm systems can be integrated with fire detection systems, intrusion detection systems, access control systems, or closed-circuit television (CCTV) systems such that these systems automatically respond when the alarm is triggered. A smoke detector alarm, for example, can be set up to automatically notify the fire department when smoke is detected, or an intrusion alarm can automatically trigger cameras to turn on in a remote location so personnel can monitor that location. An alarm system consists of sensors that detect different types of events; an arming station that is used to turn the system on and off; a control panel that receives information, processes it, and transmits the alarm; and an annunciator, which generates a visual or audible response to the alarm. When a sensor is tripped, it sends a signal to a control panel, which triggers a visual or audible alarm or notifies a central monitoring station. A more complete description of each of the components of an alarm system is provided below. Detection devices (also called sensors) are designed to detect a specific type of event (such as smoke or intrusion). Depending on the type of event they are designed to detect, sensors can be located inside or outside of the facility or other asset. When an event is detected, the sensors use some type of communication method (such as wireless radio transmitters, conductors, or cables) to send signals to the control panel to generate the alarm; for example, a smoke detector sends a signal to a control panel when it detects smoke. An arming station, which is the main user interface with

the security system, allows the user to arm (turn on), disarm (turn off), and communicate with the system. How a specific system is armed will depend on how it is used. Although intrusion detection systems can be armed for continuous operation (24 hours a day), they are usually armed and disarmed according to the work schedule at a specific location so personnel going about their daily activities do not set off the alarms. In contrast, fire protection systems are typically armed 24 hours a day. The control panel receives information from the sensors and sends it to an appropriate location, such as to a central operations station or to a 24-hour monitoring facility. When the alarm signal is received at the central monitoring location, personnel monitoring for alarms can respond (such as by sending security teams to investigate or by dispatching the fire department). The annunciator responds to the detection of an event by emitting a signal. This signal may be visual, audible, or electronic, or a combination of these three; for example, fire alarm signals will always be connected to audible annunciators, whereas intrusion alarms may not be. Alarms can be reported locally, remotely, or both locally and remotely. A local alarm emits a signal at the location of the event (typically using a bell or siren). A local-only alarm emits a signal at the location of the event but does not transmit the alarm signal to any other location (i.e., it does not transmit the alarm to a central monitoring location). Typically, the purpose of a local-only alarm is to frighten away intruders and possibly to attract the attention of someone who might notify the proper authorities. Because no signal is sent to a central monitoring location, personnel can only respond to a local alarm if they are in the area and can hear or see the alarm signal. Fire alarm systems must have local alarms, including both audible and visual signals. Most fire alarm signal and response requirements are codified in the National Fire Alarm Code, National Fire Protection Association (NFPA) 72, which discusses the application, installation, performance, and maintenance of protective signaling systems. In contrast to fire alarms, which require a local signal when fire is detected, many intrusion detection systems do not have a local alert device, because monitoring personnel do not wish to inform potential intruders that they have been detected. Instead, these types of systems silently alert monitoring personnel that an intrusion has been detected, thus allowing monitoring personnel to respond. In contrast to systems that are set up to transmit local-only alarms when the sensors are triggered, systems can also be set up to transmit signals to a central location, such as to a control room or guard post at the utility or to a police or fire station. Most fire and smoke alarms are set up to signal both at the location of the event and at a fire station or central monitoring station. Many insurance companies require that facilities install certified systems that include alarm communication to a central station; for example, systems certified by the Underwriters Laboratory (UL) require that the alarm be reported to a central monitoring station. The main differences among alarm systems lie in the types of event detection devices used in different systems. Intrusion sensors, for example, consist of two main categories: perimeter sensors and interior (space) sensors. Perimeter intrusion sensors are typically applied on fences, doors, walls, windows, etc. and are designed to detect intruders before they gain access to a protected asset (e.g., perimeter intrusion sensors are used to detect intruders attempting to enter through a door or window). In contrast, interior intrusion sensors are designed to detect an intruder who has already accessed the protected asset (i.e., interior intrusion sensors are used to detect intruders when they are already within a protected room or building). These two types of detection devices can be complementary, and they are often used together to enhance security for an asset. A typical intrusion alarm system, for example, might employ a perimeter glass-break detector that protects against intruders accessing a room through a window, as well as an ultrasonic interior sensor that detects intruders

that have gotten into the room without using the window. Fire detection and fire alarm systems consist of various combinations of fire detection devices and fire alarm systems. These systems may detect fire, heat, or smoke, or a combination of any of these. A typical fire alarm system might consist only of heat sensors located throughout a facility that detect high temperatures or a certain change in temperature over a fixed time period, whereas a different system might be outfitted with both smoke and heat detection devices.

When a sensor in an alarm system detects an event, it must communicate an alarm signal. The two basic types of alarm communication systems are hardwired and wireless. Hardwired systems rely on wire that is run from the control panel to each of the detection devices and annunciators. Wireless systems transmit signals from a transmitter to a receiver through the air—primarily using radio or other waves. Hardwired systems are usually lower cost, more reliable (they are not affected by terrain or environmental factors), and significantly easier to troubleshoot than wireless systems; however, a major disadvantage of hardwired systems is that it may not be possible to hardwire all locations (e.g., it may be difficult to hardwire remote locations). In addition, running wires to their required locations can be both time consuming and costly. The major advantage to using wireless systems is that they can often be installed in areas where hardwired systems are not feasible; however, wireless components can be much more expensive when compared to hardwired systems. Also, in the past it has been difficult to perform self-diagnostics on wireless systems to confirm that they are communicating properly with the controller. Currently, the majority of wireless systems incorporate supervising circuitry, which allows the subscriber to recognize immediately any problem with the system (such as a broken detection device or a low battery) or if a protected door or window has been left open.

Backflow Prevention Devices Backflow prevention devices are designed to prevent backflow, which is the reversal of the normal and intended direction of water flow in a water system. Backflow is a potential problem in a water system because it can spread contaminated water back through a distribution system. For example, pollution or backflow at uncontrolled cross-connections (any actual or potential connection between the public water supply and a source of contamination) can allow pollutants or contaminants to enter the potable water system. More specifically, backflow from private plumbing systems, industrial areas, hospitals, and other hazardous contaminant-containing systems into public water mains and wells poses serious public health risks and security problems. Cross-contamination from private plumbing systems can contain biological hazards (such as bacteria or viruses) or toxic substances that can contaminate and sicken an entire population in the event of backflow. The majority of historical incidences of backflow have been accidental, but growing concern that contaminants could be intentionally backfed into a system is prompting increased awareness among private homeowners, businesses, industries, and areas most vulnerable to intentional strikes; therefore, backflow prevention is a major component of water system protection. Backflow may occur under two types of conditions: backpressure and backsiphonage. Backpressure is a reversal of normal flow direction within a piping system resulting from the downstream pressure being higher than the supply pressure. These reductions in the supply pressure occur whenever the amount of water being used exceeds the amount of water supplied, such as during water-main flushing, fire fighting, or breaks in water mains. Backsiphonage is a reversal of normal flow direction within a piping system caused by negative pressure in the supply piping (the reversal of normal flow in a system caused by a vacuum or partial vacuum within the water supply piping). Backsiphonage can occur due to high velocity in a pipeline, a line repair or break that is lower than a service point, or a lowered main pressure caused by a

high water withdrawal rate, such as during fire fighting or water-main flushing. To prevent backflow, various types of backflow preventers are appropriate for use. The primary types of backflow preventers are

- Air gap drains
- Double check valves
- Reduced pressure principle assemblies
- Pressure vacuum breakers

Biometric Security Systems Biometrics involves measuring the unique physical characteristics or traits of the human body. Any aspect of the body that is measurably different from person to person—for example, fingerprints or eye characteristics—can serve as unique biometric identifiers for individuals. Biometric systems recognizing fingerprints, palm shape, eyes, face, voice, and signature comprise the bulk of the current biometric systems. Biometric security systems use biometric technology combined with some type of locking mechanism to control access to specific assets. To access an asset that is controlled by a biometric security system, an individual's biometric trait must be matched with an existing profile stored in a database. If a match between the two is identified, the locking mechanism (e.g., a physical lock at a doorway, an electronic lock at a computer terminal) is disengaged, and the individual is given access to the asset. A biometric security system is typically comprised of the following components:

- A sensor measures and records a biometric characteristic or trait.
 - A control panel serves as the connection point between various system components. The control panel communicates information back and forth between the sensor and the host computer and controls access to the asset by engaging or disengaging the system lock based on internal logic and information from the host computer.
 - A host computer processes and stores the biometric trait in a database.
 - Specialized software compares an individual image taken by the sensor with stored profiles.
 - A locking mechanism is controlled by the biometric system.
 - A power source supplies power to the system.
- Biometric Hand and Finger Geometry Recognition** Hand and finger geometry recognition is the process of identifying an individual through the unique geometry (e.g., shape, thickness, length, width) of that individual's hand or fingers. Hand geometry recognition has been employed since the early 1980s and is a widely used biometric technologies for controlling access to important assets. It is simple to install and use and is appropriate for any location requiring highly accurate biometric security; for example, it is currently used in numerous workplaces, daycare facilities, hospitals, universities, airports, and power plants. One option within hand geometry recognition technology is finger geometry recognition (not to be confused with fingerprint recognition). Finger geometry recognition relies on the same scanning methods and technologies as does hand geometry recognition, but the scanner scans only two of the user's fingers, as opposed to the entire hand. Finger geometry recognition has been in commercial use since the mid-1990s and is mainly used in time and attendance applications (i.e., to track when individuals have entered and exited a location). The first large-scale commercial application of two-finger geometry was at Disney World to control access to the park. Season-pass holders used the geometry of their index and middle finger to gain access to the facilities, but today single finger scanners are used. Hand and finger geometry recognition systems can be used in several different types of applications, including access control and time and attendance tracking. Although time and attendance tracking can be used for security purposes, it is primarily used in operations and payroll areas (e.g., clocking in and clocking out). In contrast, access control applications are more likely to be security related. Biometric systems are widely used for access control and can be used to protect various types of assets, including entryways, computers, and vehicles. Because of their size, however, hand and finger recognition systems are primarily limited to use in entryway access control applications.
- Biometric Iris Recognition** The iris is the colored or pigmented area of the eye surrounded by the sclera (the white portion of the eye); it is a mus-

cular membrane that controls the amount of light entering the eye by contracting or expanding the pupil (the dark center of the eye). The dense, unique patterns of connective tissue in the human iris were first noted in 1936, but it was not until 1994, when algorithms for iris recognition were created and patented, that commercial applications using biometric iris recognition began to be used extensively. Several vendors are producing iris recognition technology, including the original developer of these algorithms as well as companies that have developed and patented different sets of algorithms for iris recognition. The iris is an ideal characteristic for identifying individuals because it is formed in utero, and its unique patterns stabilize around 8 months after birth. No two irises are alike—neither an individual's right and left irises nor the irises of identical twins. The iris is protected by the cornea (the clear covering over the eye); therefore, it is not subject to the aging or physical changes (and potential variation) that are common to some other biometric measures, such as the hand, fingerprints, and the face. Although some limited changes can occur naturally over time, these changes generally occur in the melanin of the iris and therefore affect only the eye's color, not its unique patterns. Because iris scanning uses only black and white images, color changes do not affect the effectiveness of the scan. Barring specific injuries or surgeries directly affecting the iris, the unique patterns of the iris remain relatively unchanged over an individual's lifetime. Iris recognition systems employ a monochromatic, or black and white, video camera that uses both visible and near-infrared light to take a video of an individual's iris. Video is used rather than still photography as an extra security procedure. The video is used to confirm the normal continuous fluctuations of the pupil as the eye focuses, which ensures that the scan is of a living human being and not a photograph or some other attempted hoax. A high-resolution image of the iris is then captured or extracted from the video using a device often referred to as a frame grabber. The unique characteristics identified in this image are then converted into a numeric code, which is stored as a template for that user.

Card Identification and Access Tracking Systems A card reader system is a type of electronic identification system that is used to read a card and then perform an action associated with that card. Depending on the system, the card may identify where a person is or where they were at a certain time, or it may authorize another action such as disengaging a lock. Security guards, for example, may use their cards at card readers located throughout a facility to indicate that they have checked certain locations at certain times. The reader will store the information or send it to a central location where the data can be checked later to verify that various areas in the facility have been patrolled. Other card reader systems can be associated with a lock, such that cardholders must have their cards read and accepted by the reader before the lock disengages. A complete card reader system typically consists of the following components:

- Access cards carried by the user
- Card readers, which read the card signals and send the information to control units
- Control units, which control the response of the card reader to the card
- A power source

Numerous types of card reader systems are available. All card systems are similar with regard to how the card reader and control unit interact; however, they differ in how data are encoded on the cards and are transferred between the cards and the card readers, which determines the types of applications for which they are best suited. Several types of technologies are available for card reader systems, including the following:

- Proximity
- Wiegand
- Smartcard
- Magnetic stripe
- Bar code
- Infrared
- Barium ferrite
- Hollerith
- Mixed technologies

The level of security required (low, moderate, or high) affects the choice of card technology (e.g., how sim-

ple is it to duplicate a particular technology and thus bypass the security system). Vulnerability ratings are based on how easily the card reader can be damaged due to frequent use or challenging working conditions (e.g., weather conditions if the reader is located outside). Often, the vulnerability of a system is influenced by the number of moving parts in the system—the more moving parts, the greater the potential susceptibility to damage. Life-cycle ratings are based on the durability of a given card reader system over its entire operational period. Systems requiring frequent physical contact between the reader and the card often have a shorter life cycle due to the wear and tear to which the equipment is exposed. For many card reader systems, the vulnerability rating and life-cycle ratings have a reciprocal relationship; for example, if a given system has a high vulnerability rating it will almost always have a shorter life cycle. Card reader technology can be implemented for facilities of any size and with any number of users; however, because individual systems vary in the complexity of their technology and the level of security they can provide to a facility, individual users must determine the appropriate system for their needs. Some important questions to consider when selecting a card reader system include the following:

- What level of technological sophistication and security does the card system have?
- How large is the facility, and what are its security needs?
- How frequently will the card system be used? For systems that will experience a high frequency of use, it is important to consider a system that has a longer life cycle and lower vulnerability rating, thus making it more cost effective to implement.
- Under what conditions will the system be used? For example, will it be installed on the interior or exterior of buildings? Does it require light or humidity controls? Most card reader systems can operate under normal environmental conditions; therefore, this would be a mitigating factor only in extreme conditions.
- What are the system costs?

Exterior Intrusion Sensors Exterior vs. Interior Intrusion Sensors An exterior intrusion sensor is a detection device used in an outdoor environment to detect intrusions into a protected area. Intrusion sensors are designed to detect an intruder and then communicate an alarm signal to an alarm system. The alarm system can respond to the intrusion in many different ways, such as by triggering an audible or visual alarm signal or by sending an electronic signal to a central monitoring location that notifies security personnel of the intrusion. Intrusion sensors can be used to protect many kinds of assets. Intrusion sensors that protect physical space are classified according to whether they protect indoor, or interior, spaces (e.g., an entire building or room within a building), or outdoor, or exterior, spaces (e.g., a fence line or perimeter). Interior intrusion sensors are designed to protect the interior space of a facility by detecting an intruder who is attempting to enter or who has already entered a room or building. In contrast, exterior intrusion sensors are designed to detect an intrusion into a protected outdoor/exterior area. Exterior protected areas are typically arranged as zones or exclusion areas placed so the intruder is detected early in the intrusion attempt before gaining access to more valuable assets (e.g., into a building located within the protected area). Early detection creates additional time for security forces to respond to the alarm.

Buried Exterior Intrusion Sensors Buried sensors are electronic devices that are designed to detect potential intruders. The sensors are buried along the perimeters of sensitive assets and are able to detect intruder activity both above and below-ground. Some of these systems are composed of individual, stand-alone sensor units, while other sensors consist of buried cables. **Fences** A fence is a physical barrier that can be set up around the perimeter of an asset. Fences often consist of individual pieces (such as individual pickets in a wooden fence or individual sections of a wrought iron fence) that are fastened together. Individual sections of the fence are fastened together using posts, which are sunk into the ground to pro-

vide stability and strength for the sections of the fence hung between them. Gates are installed between individual sections of the fence to allow access inside the fenced area. Fences are often used as decorative architectural features to separate physical spaces from each other and to mark the location of a boundary (such as a fence installed along a property line); however, a fence can also serve as an effective means for preventing intruders from gaining access to a water or wastewater asset. Many utilities install fences around their primary facilities, around remote pump stations, or around hazardous materials storage areas or sensitive areas within a facility. Access to the area can be controlled through security located at gates or doors in the fence (e.g., posting a guard at the gate or locking it). To gain access to the asset, unauthorized persons would have to find a way either around or through the fence. Fences are often compared with walls when determining the appropriate system for perimeter security. Both fences and walls can provide adequate perimeter security, and fences are often easier and less expensive to install than walls; however, they do not usually provide the same physical strength that walls do. In addition, many types of fences have gaps between the individual pieces that make up the fence (e.g., the spaces between chain links in a chain-link fence or the space between pickets in a picket fence); thus, many types of fences allow the interior of the fenced area to be seen. This may allow intruders to gather important information about the locations or defenses of vulnerable areas within the facility. Numerous types of materials are used to construct fences, including chain link iron, aluminum, wood, or wire. Some types of fences, such as split rails or pickets, may not be appropriate for security purposes because they are traditionally low fences, and they are not physically strong. Potential intruders may be able to easily defeat these fences either by jumping or climbing over them or by breaking through them; for example, the rails in a split fence may be able to be broken easily. Important security features of a fence include the height to which it can be constructed, the strength of the material comprising the fence, the method and strength of attaching the individual sections of the fence together at the posts, and the ability of the fence to restrict the view of the assets inside the fence. Additional considerations include the ease of installing the fence and the ease of removing and reusing sections of the fence. Some fences can include additional measures to delay, or even detect, potential intruders. Such measures may include the addition of barbed wire, razor wire, or other deterrents at the top of the fence. Barbed wire employed at the base of a fence can also impede a would-be intruder's access to the fence. Fences can be fitted with security cameras to provide visual surveillance of the perimeter, and some facilities have installed motion sensors along their fences to detect movement on the fence. Several manufacturers have combined these multiple perimeter security features into one product and offer alarms and other security features. The correct implementation of a fence can make it a much more effective security measure. Security experts recommend the following when a facility constructs a fence:

- The fence should be at least 7 to 9 feet high.
- Any outriggers, such as barbed wire, that are affixed on top of the fence should be angled out and away from the facility, not in toward the facility. This will make climbing the fence more difficult and will prevent the placement of ladders against the fence.
- Other types of hardware that can increase the security of the fence include installing concertina wire along the fence (this can be done in front of the fence or at the top of the fence) or adding intrusion sensors, camera, or other hardware to the fence.
- All undergrowth should be cleared for several feet (typically 6 feet) on both sides of the fence. This will allow for a clearer view of the fence by any patrols in the area.
- Any trees with limbs or branches hanging over the fence should be trimmed so intruders cannot use them to go over

the fence. Also, it should be noted that fallen trees can damage fences, so management of trees around the fence can be important. This can be especially important in areas where the fence runs through a remote area. • Fences that do not block the view from outside the fence allow security patrols to see inside the fence without having to enter the facility. • “No Trespassing” signs posted along a fence can be a valuable tool in prosecuting any intruders who claim that the fence was broken and that they did not enter through the fence illegally. Adding signs that highlight the local ordinances against trespassing can further dissuade simple troublemakers from illegally climbing the fence.

Films for Glass Shatter Protection Most water utilities have numerous windows on the outside of buildings, in doors, and in interior offices. In addition, many facilities have glass doors or other glass structures, such as glass walls or display cases. These glass objects are potentially vulnerable to shattering when heavy objects are thrown or launched at them, when explosions occur near them, or when there are high winds. If the glass is shattered, intruders may potentially enter an area. In addition, shattered glass projected into a room from an explosion or from an object being thrown through a door or window can injure and potentially incapacitate personnel in the room. Materials that prevent glass from shattering can help to maintain the integrity of the door, window, or other glass object and can delay an intruder from gaining access. These materials can also prevent flying glass and thus reduce potential injuries. Materials designed to prevent glass from shattering include specialized films and coatings. These materials can be applied to existing glass objects to improve their strength and their ability to resist shattering. The films have been tested against many scenarios that could result in glass breakage, including penetration by blunt objects, bullets, high winds, and simulated explosions. They are tested against simulated weather scenarios (including high winds and the force of objects blown into the glass), as well as criminal or terrorist scenarios where the glass could be subject to explosives or bullets. Many vendors provide information on the results of these types of tests so potential users can compare different product lines to determine which products best suit their needs. The primary considerations with regard to films for shatter protection are

- The materials from which the film is made
- The adhesive that bonds the film to the glass surface
- The thickness of the film

Fire Hydrant Locks Fire hydrants are installed at strategic locations throughout a community’s water distribution system to supply water for fire fighting. Because the many hydrants in a system are often located in residential neighborhoods, industrial districts, and other areas where they cannot be easily observed or guarded, they are potentially vulnerable to unauthorized access. Many municipalities, states, and USEPA regions have recognized this potential vulnerability and have instituted programs to lock hydrants; for example, USEPA Region 1 includes locking hydrants as the seventh item in its Drinking Water Security and Emergency Preparedness “top ten” list for small groundwater suppliers. A hydrant lock is a physical security device designed to prevent unauthorized access to the water supply through a hydrant. Such locks can ensure water and water pressure availability to fire fighters and prevent water theft and associated lost water revenue. These locks have been used successfully in numerous municipalities and in various climates and weather conditions. Fire hydrant locks are basically steel covers or caps that are locked in place over the operating nut of a fire hydrant. The lock prevents unauthorized persons from accessing the operating nut and opening the fire hydrant valve. The lock also makes it more difficult to remove the bolts from the hydrant and access the system that way. Finally, hydrant locks shield the valve

from being broken off. Should a vandal attempt to breach the hydrant lock by force and succeed in breaking the hydrant lock, the vandal will only succeed in bending the operating valve. If the operating valve of the hydrant is bent, the hydrant will not be operational, but the water asset remains protected and inaccessible to vandals; however, the entire hydrant will have to be replaced. The locking mechanisms for fire hydrant locking systems ensure that hydrants can only be accessed by authorized personnel who have the special key wrench required to operate a hydrant without removing the lock. These specialized wrenches are generally distributed to the fire department, public works department, and other authorized persons so they can access the hydrants as needed. An inventory of wrenches and their serial numbers is generally kept by a municipality so the location of all wrenches is known. These operating key wrenches may only be purchased by registered lock owners. The most important features of hydrant are their strength and the security of their locking systems. The locks must be strong so they cannot be broken off. Hydrant locks are constructed from stainless or alloyed steel. Stainless-steel locks are stronger and are ideal for all climates; however, they are more expensive than alloy locks.

A hatch is basically a door installed on a horizontal plane (such as in a floor, a paved lot, or a ceiling), instead of on a vertical plane (such as in a building wall). Hatches are usually used to provide access to assets that are located underground (e.g., in basements or underground storage areas) or above ceilings (such as emergency roof exits). At water and wastewater facilities, hatches are typically used to provide access to underground vaults containing pumps, valves, or piping, or to the interior of water tanks or covered reservoirs. Securing a hatch by locking it or upgrading materials to give the hatch added strength can help to delay unauthorized access to any asset behind the hatch. Like all doors, a hatch consists of a frame anchored to the horizontal structure, a door or doors, hinges connecting the door to the frame, and a latching or locking mechanism that keeps the hatch door closed. It should be noted that improving hatch security is straightforward and that hatches with upgraded security features can be installed new or they can be retrofit for existing applications. Many municipalities already have specifications for hatch security at their water and wastewater utility assets. Depending on the application, the primary security-related attributes of a hatch are the strength of the door and frame, its resistance to the elements and corrosion, its ability to be sealed against water or gas, and its locking features. Hatches must be both strong and lightweight so that they can withstand typical static loads (such as people or vehicles walking or driving over them) while still being easy to open. In addition, because hatches are typically installed at outdoor locations, they are usually fabricated out of corrosion-resistant metal that can withstand the elements such as high-gauge steel or lightweight aluminum. The hatch locking mechanism is perhaps the most important component of hatch security. A number of locks can be implemented for hatches, including

- Slam locks (internal locks located within the hatch frame)
- Recessed cylinder locks
- Bolt locks
- Padlocks

Ladder Access Control Water and wastewater utilities have a number of assets that are raised above ground level, including raised water tanks, raised chemical tanks, raised piping systems, and roof access points into buildings. In addition, communications equipment, antennae, or other electronic devices may be located on the top of these raised assets. Typically, these assets are reached by ladders that are permanently anchored to the asset; for example, raised water tanks typically are accessed by ladders that are bolted to one of the legs of the tank. Controlling access to these raised assets by controlling access to the ladder can increase security at a water or wastewater utility. A typical ladder access control system consists of some type of cover that is locked or secured over the ladder. The cover can be a casing that surrounds most of

the ladder or a door or shield that covers only part of the ladder. In either case, several rungs of the ladder (the number of rungs depends on the size of the cover) are made inaccessible by the cover, and these rungs can only be accessed by opening or removing the cover. The cover is locked so only authorized personnel can open or remove it and use the ladder. Ladder access controls are usually installed at several feet above ground level, and they usually extend several feet up the ladder so they cannot be circumvented by someone accessing the ladder above the control system. The covers are constructed from aluminum or some type of steel. This should provide adequate protection from being pierced or cut through. The metals are corrosion resistant so they will not corrode or become weakened due to extreme weather conditions in outdoor applications. The bolts used to install each of these systems are galvanized steel. In addition, the bolts for each cover are installed on the inside of the unit so they cannot be removed from the outside. The important features of ladder access control are the size and strength of the cover and the ability to lock or otherwise secure the cover from unauthorized access.

Locks A lock is a type of physical security device that can be used to delay or prevent the opening, moving, or operation of a door, window, manhole, filing-cabinet drawer, or some other physical feature. Locks typically operate by connecting two pieces together, such as connecting a door to a door jamb or a manhole to its casement. Every lock has two modes: engaged (or locked) and disengaged (or opened). When a lock is disengaged, the asset on which the lock is installed can be accessed by anyone, but when the lock is engaged, only access to the locked asset. Locks are excellent security features because they have been designed to function in many ways and to work on many different types of assets. Locks can also provide different levels of security depending on how they are designed and implemented. The security provided by a lock is dependent on several factors, including its ability to withstand physical damage (e.g., being cut off, broken, or otherwise physically disabled) as well as its requirements for supervision or operation (e.g., combinations may have to be changed frequently so they are not compromised and the locks remain secure). Although no agreed-upon rating of lock security exists, locks are often designated as being minimum, medium, or maximum security. Minimum security locks are those that can be easily disengaged (or “picked”) without the correct key or code or those that can be disabled easily (such as small padlocks that can be cut with bolt cutters). Higher security locks are more complex and thus are more difficult to pick, or they are sturdier and more resistant to physical damage. Many locks only have to be unlocked from one side; for example, most door locks (single-cylinder locks) can be opened on the outside by inserting a key in the lock. On the inside, a person can unlock the same lock by pushing a button or turning a knob or handle. Double cylinder locks require a key to be locked or unlocked from both sides.

Manhole Intrusion Sensors Manholes are located at strategic locations throughout most municipal water, wastewater, and other underground utility systems. Manholes are designed to provide access to underground utilities, and they represent potential entry points to a system; for example, manholes in water or wastewater systems may provide access to sewer lines or vaults containing on/off or pressure-reducing water valves. Because many utilities run under other infrastructure (roads, building), manholes also provide potential access points to critical infrastructure as well as water and wastewater assets. In addition, because the portion of the system to which manholes provide entry is primarily located underground, access to a system through a manhole increases the chances that an intruder will not be seen; therefore, protecting manholes can be a critical component of guarding an entire community. The various methods for protecting manholes are designed to prevent unauthorized personnel from physically accessing the man-

hole or to detect attempts at unauthorized access to the manhole. A manhole intrusion sensor is a physical security device designed to detect unauthorized access to the utility through a manhole. Monitoring a manhole that provides access to a water or wastewater system can mitigate two distinct types of threats. First, monitoring a manhole may detect access of unauthorized personnel to water or wastewater systems or assets through the manhole. Second, monitoring manholes may also allow the detection of the introduction of hazardous substances into the water system. Several different technologies have been used for manhole intrusion sensors, including mechanical systems, magnetic systems, and fiberoptic and infrared sensors. Some of these intrusion sensors have been specifically designed for manholes, while others consist of standard, off-the-shelf intrusion sensors that have been implemented in a system specifically designed for application in a manhole.

Manhole Locks A manhole lock is a physical security device designed to delay unauthorized access to the utility through a manhole. Locking a manhole that provides access to a water or wastewater system can mitigate two distinct types of threats. First, locking a manhole may delay access of unauthorized personnel to water or wastewater systems through the manhole. Second, locking manholes may also prevent the introduction of hazardous substances into the wastewater or stormwater system.

Radiation Detection Equipment for Monitoring Personnel and Packages A major potential threat that water and wastewater facilities face is contamination by radioactive substances. Radioactive substances brought on-site at a facility could be used to contaminate the facility, thereby preventing workers from safely entering the facility to perform necessary water treatment tasks. In addition, radioactive substances brought onsite at a water treatment plant could be discharged into the water source or the distribution system, contaminating the downstream water supply; therefore, detection of radioactive substances being brought on-site can be an important security enhancement. Various radionuclides have unique properties, and different equipment is required to detect the different types of radiation; however, it is impractical and potentially unnecessary to monitor for specific radionuclides. Instead, for security purposes, it may be more useful to monitor for gross radiation as an indicator of unsafe substances. To protect against radioactive materials being brought onsite, a facility may set up monitoring sites outfitted with radiation detection instrumentation at entrances to the facility. Depending on the specific types of equipment chosen, this equipment would detect radiation emitted from people, packages, or other objects being brought through an entrance. One of the primary differences between the various types of detection equipment is the means by which the equipment reads the radiation. Radiation may be detected by direct measurement or through sampling. Direct radiation measurement involves measuring radiation through an external probe on the detection instrumentation. Some direct measurement equipment detects radiation emitted into the air around the monitored object. Because this equipment detects radiation in the air, it does not require that the monitoring equipment make physical contact with the monitored object. Direct means for detecting radiation include using either a walk-through, portal-type monitor that detects elevated radiation levels on a person or in a package or a hand-held detector, which would be moved or swept over individual objects to locate an radioactive source. Some types of radiation, such as alpha or low-energy beta radiation, have a short range and are easily shielded by various materials. These types of radiation cannot be measured through direct measurement. Instead, they must be measured through sampling. Sampling involves wiping the surface to be tested with a special filter cloth and then exposing the cloth to a special counter; for example, specialized smear counters measure alpha and low-energy beta radiation.

Reservoir Covers Reservoirs are used to store raw or untreated water. They can be located underground (buried), at ground level, or on an elevated surface. Reservoirs can vary significantly in size; small reservoirs can hold as little as 1000 gallons, and larger reservoirs may hold many millions of gallons. Reservoirs can be either natural or manmade. Natural reservoirs can include lakes or other contained water bodies, whereas manmade reservoirs usually consist of some sort of engineered structure, such as a tank or other impoundment structure. In addition to the water containment structure itself, reservoir systems may also include associated water treatment and distribution equipment, including intakes, pumps, pump houses, piping systems, chemical treatment, and chemical storage areas. Drinking water reservoirs are of particular concern because they are potentially vulnerable to contamination of the stored water, through direct contamination of the storage area or via infiltration of the equipment, piping, or chemicals associated with the reservoir. Because many drinking water reservoirs are designed as aboveground, open-air structures, they are potentially vulnerable to airborne deposition, bird and animal wastes, human activities, and dissipation of chlorine or other treatment chemicals; however, one of the most serious potential threats to the system is direct contamination of the stored water through the dumping of contaminants into the reservoir. Utilities have taken various measures to mitigate this type of threat, including fencing off the reservoir, installing cameras to monitor for intruders, and monitoring for changes in water quality. Another option for enhancing security is covering the reservoir using some type of manufactured cover to prevent intruders from gaining physical access to the stored water. Implementing a reservoir cover may or may not be practical depending on the size of the reservoir; covers are not typically used on natural reservoirs because they are too large for the cover to be technically feasible and cost effective. This section focuses on drinking-water reservoir covers, where and how they are typically implemented, and how they can be used to reduce the threat of contamination of the stored water. Although covers can enhance the security of a reservoir, it should be noted that covering a reservoir typically changes the operational requirements of the reservoir; for example, vents must be installed in the cover to ensure gas exchange between the stored water and the atmosphere. A reservoir cover is a structure installed on or over the surface of the reservoir to minimize water quality degradation. The three basic types of reservoir covers are

- Floating
- Fixed
- Air-supported

Various materials are used to manufacture a cover, including reinforced concrete, steel, aluminum, polypropylene, chlorosulfonated polyethylene, or ethylene interpolymer alloys. Several factors affect the effectiveness of a reservoir cover and thus its ability to protect the stored water, including

- The location, size, and shape of the reservoir
- The ability to lay or support a foundation (e.g., footing, soil, and geotechnical support conditions)
- The length of time reservoir can be removed from service for cover installation or maintenance
- Aesthetic considerations
- Economic factors, such as capital and maintenance costs

It may not be practical, for example, to install a fixed cover over a reservoir if the reservoir is too large or if the local soil conditions cannot support a foundation. A floating or air-supported cover may be more appropriate for these types of applications. In addition to the practical considerations for installation of these types of covers, a number of operations and maintenance (O&M) concerns can affect the utility of a cover for specific applications, including how the various cover materials available will withstand local climatic conditions, what types of cleaning and maintenance will be required for each particular type of cover, and how these factors will affect the covers lifespan and its ability to be repaired when it is damaged.

The primary feature affecting the security of a reservoir cover is its ability to maintain its integrity. Any type of cover, no matter what its construction material, will provide good protection from contamination by rainwater or atmospheric deposition, as well as from intruders attempting to access the stored water with the intent of causing intentional contamination. The covers are large and heavy, and it is difficult to circumvent them to get into the reservoir. At the very least, it would take a determined intruder, as opposed to a vandal, to defeat the cover.

Security Barriers: Active and Passive One of the most basic threats facing any facility is from intruders accessing the facility with the intention of causing damage to its assets. These threats may include intruders actually entering the facility, as well as intruders attacking the facility from outside without actually entering it (e.g., detonating an explosive near enough to the facility to cause damage within its boundaries). Security barriers are one of the most effective ways to counter the threat of intruders accessing a facility or the facility perimeter. Security barriers are large, heavy structures used to control access through a perimeter by either vehicles or personnel. They can be used in many different ways depending on how they are installed or where they are located at the facility; for example, security barriers can be used on or along driveways or roads to direct traffic to a checkpoint (e.g., placement of jersey barriers to direct traffic in particular direction). Other types of security barriers (e.g., crash beams, gates) can be installed at the checkpoint so guards can regulate which vehicles can access the facility. Finally, security barriers (e.g., bollards, security planters) can be used along the facility perimeter to establish a protective buffer area between the facility and approaching vehicles. Establishing such a protective buffer can help in mitigating the effects of an explosive by potentially absorbing some of the blast and by increasing the stand-off distance between the blast and the facility. The force of an explosion is reduced as the shock wave travels away from the source; thus, the greater the distance between the target and an explosion, the less damage will be incurred. Security barriers can be either active or passive. Active security barriers, which include gates, retractable bollards, wedge barriers, and crash barriers, are readily movable and are typically used in areas where they must be moved often to allow vehicles to pass—such as in roadways at entrances and exits to a facility. In contrast to active security barriers, passive security barriers, which include jersey barriers, bollards, and security planters, are not designed to be moved on a regular basis and are typically used in areas where access is not required or allowed—such as along building perimeters or in traffic-control areas. Passive security barriers are typically large, heavy structures that are usually several feet high, and they are designed so even heavy-duty vehicles cannot go over or through them. They can be placed in a roadway parallel to the flow of traffic so they direct traffic in a particular direction (such as to a guardhouse, a gate, or some other sort of checkpoint) or perpendicular to traffic such that they prevent a vehicle from using a road or approaching a building or area.

Security for Doorways: Side-Hinged Doors Doorways are the main access points to a facility or to rooms within a building. They are used on the exterior or in the interior of buildings to provide privacy and security for the areas behind them. Different types of doorway security systems may be installed in various doorways depending on the requirements of the building or room. For example, exterior doorways tend to have heavier doors to withstand the elements and to provide some security to the entrance of the building. Interior doorways in office areas may have lighter doors that may be primarily designed to provide privacy rather than security; these doors may be made of glass or lightweight wood. Doorways in industrial areas may have sturdier doors than do other interior doorways and may be designed to provide protection

or security for areas behind the doorway; for example, fireproof doors may be installed in chemical storage areas or in other areas where there is a danger of fire. Because they are the main entries into a facility or a room, doorways are often prime targets for unauthorized entry into a facility or an asset; therefore, securing doorways may be a major step in providing security at a facility. A doorway includes four main components:

- The door, which blocks the entrance. The primary threat to the actual door is breaking or piercing through it; therefore, the primary security features of doors are their strength and resistance to various physical threats, such as fire or explosions.
- The door frame, which connects the door to the wall. The primary threat to a door frame is that the door can be pried away from the frame; therefore, the primary security feature of a door frame is its resistance to prying.
- The hinges, which connect the door to the door frame. The primary threat to door hinges is that they can be removed or broken, which will allow intruders to remove the entire door; therefore, security hinges are designed to be resistant to breaking. They may also be designed to minimize the threat of removal from the door.
- The lock, which connects the door to the door frame. Use of the lock is controlled through various security features, such as keys, combinations, etc., such that only authorized personnel can open the lock and go through the door. Locks may also incorporate other security features, such as software to track overall use of the door or to track individuals using the door.

Each of these components is integral to providing security for a doorway. Upgrading the security of only one of these components while leaving the other components unprotected may not improve the overall security of the doorway. Many facilities upgrade door locks as a basic step toward increasing their security, but if a facility does not also modify the door hinges or the door frame then the door may remain vulnerable to being removed from its frame, thus defeating the purpose of installing the new door lock. The primary attribute for the security of a door is its strength. Many security doors are 4 to 20-gauge hollow metal doors consisting of steel plates over a hollow cavity reinforced with steel stiffeners to give the door extra stiffness and rigidity. This increases resistance to any blunt force applied in an attempt to penetrate through the door. The space between the stiffeners may be filled with specialized materials to provide fire, blast, or bullet resistance to the door. The Window and Door Manufacturers Association has developed a list of performance attributes for doors:

• Structural resistance • Forced-entry resistance • Hinge-style screw resistance • Split resistance • Hinge resistance • Security rating • Fire resistance • Bullet resistance • Blast resistance

The first five items relate to the resistance of a door to standard physical breaking and prying attacks. Tests are used to evaluate the strength of the door and the resistance of the hinges and the frame in a standardized way. The rack load test simulates a prying attack on a corner of the door. A test panel is restrained at one end, and a third corner is supported; loads are applied and measured at the fourth corner. The door impact test uses a steel pendulum to simulate a battering attack on a door and frame with impacts of 200 ft-lb; the door must remain fully operable after the test. It should be noted that door glazing is also rated for resistance to shattering, etc. Manufacturers will be able to provide security ratings for these features of a door, as well. Door frames are an integral part of doorway security because they anchor the door to the wall. Door frames are typically constructed from wood or steel, and they are installed such that they extend for several inches over the doorway that has been cut into the wall. For added security, frames can be designed to have varying degrees of overlap or wrapping. This overlap can make prying the frame from the wall more difficult. A frame formed from a continuous piece of metal (as opposed to

a frame constructed from individual metal pieces) will prevent prying between pieces of the frame. Many security doors can be retrofit into existing frames; however, many security door installations require replacement of the door frame as well as the door itself. Bullet resistance per the Underwriters Laboratory (UL) 752 standard encompasses the resistance of the door and frame assembly both; thus, replacing the door only would not meet UL 752 requirements.

Valve Lockout Devices Valves are utilized as control elements in water and wastewater process piping networks. They regulate the flow of both liquids and gases by opening, closing, or obstructing a flow passage-way. Valves are typically located where flow control is necessary; they can be located inline or at pipeline and tank entrance and exit points. Valves serve multiple purposes in a process pipe network, including

- Redirecting and throttling flow
- Preventing backflow
- Shutting off flow to a pipeline or tank (for isolation purposes)
- Releasing pressure
- Draining extraneous liquid from pipelines or tanks
- Introducing chemicals into the process network
- Serving as access points for sampling process water

Valves are located at critical junctures throughout water and wastewater systems, both on-site at treatment facilities and off-site within water distribution and wastewater collection systems. They may be located either above or below ground. Because many valves are located within the community, it is critical to provide protection against valve tampering. Tampering with a pressure-relief valve, for example, could result in a pressure buildup and potential explosion in the piping network. On a larger scale, addition of a pathogen or chemical to the water distribution system through an unprotected valve could result in the release of that contaminant to the general population. Various security products are available to protect aboveground vs. belowground valves; for example, valve lockout devices can protect valves and valve controls located above ground. Vaults containing underground valves can be locked to prevent access to these valves. Valve-specific lockout devices are available in a variety of colors, which can be useful in distinguishing different valves. Different colored lockouts can be used to distinguish the type of liquid passing through the valve (e.g., treated, untreated, potable, chemical) or to identify the party responsible for maintaining the lockout. Implementing a system of colored locks on operating valves can increase system security by reducing the likelihood of an operator inadvertently opening the wrong valve and causing a problem in the system.

Vent Security Vents are installed in aboveground, covered water reservoirs and in underground reservoirs to allow ventilation of the stored water. Specifically, vents permit the passage of air that is being displaced from, or drawn into, the reservoir as the water level in the reservoir rises and falls due to system demands. Small reservoirs may require only one vent, whereas larger reservoirs may have multiple vents throughout the system. The specific vent design for any given application will vary depending on the design of the reservoir, but every vent consists of an open-air connection between the reservoir and the outside environment. These air-exchange vents are an integral part of covered or underground reservoirs, but they also represent a potential security threat. Improving vent security by making the vents tamper resistant or by adding other security features, such as security screens or security covers, can enhance the security of the entire water system. Many municipalities already have specifications for vent security at their water assets. These specifications typically include the following requirements:

- Vent openings are to be angled down or shielded to minimize the entrance of surface water or rainwater through the opening.
- Vent designs are to include features that exclude insects, birds, animals, and dust.
- Corrosion-resistant materials are to be used to construct the vents.

Some states have adopted more specific requirements for added vent security at their water utility assets. The State of Utah's Department of Environmental Quality, Division of Drinking Water, Division of Administrative Rules (DAR), provides specific requirements for public drinking water storage tanks. The rules for drinkingwater storage tanks as they apply to venting are set forth in R309-545-15 (Venting) and include the following requirements:

- Drinking water storage tank vents must have an open discharge on buried structures.
- The vents must be located 24 to 36 inches above the earthen covering.
- The vents must be located and sized to avoid blockage during winter conditions.

In a second example, Washington State's "Drinking Water Tech Tips: Sanitary Protection of Reservoirs" document states that vents must be protected to prevent the water supply from being contaminated. The document indicates that non-corrodible No. 4 mesh may be used to screen vents on elevated tanks. The document continues to state that the vent opening for storage facilities located underground or at ground level should be 24 to 36 inches above the roof or ground and that it must be protected with a No. 24 inch mesh non-corrodible screen. New Mexico's administrative Code also specifies that vents must be covered with No. 24 mesh (NMAC Title 20, Chapter 7, Subpart I, 208.E). Washington and New Mexico, as well as many other municipalities, require vents to be screened using a non-corrodible mesh to minimize the entry of insects, other animals, and rainborne contamination into the vents. When selecting the appropriate mesh size, it is important to identify the smallest mesh size that meets both the strength and durability requirements for that application.

Visual Surveillance Monitoring Visual surveillance is used to detect threats through continuous observation of important or vulnerable areas of an asset. The observations can also be recorded for later review or use (e.g., in court proceedings). Visual surveillance system can be used to monitor various parts of collection, distribution, or treatment systems, including the perimeter of a facility, outlying pumping stations, or entry or access points into specific buildings. These systems are also useful in recording individuals who enter or leave a facility, thereby helping to identify unauthorized access. Images can be transmitted live to a monitoring station, where they can be monitored in real time, or they can be recorded and reviewed later. Many facilities have found that a combination of electronic surveillance and security guards provides an effective means of facility security. Visual surveillance is provided through a closedcircuit television (CCTV) system, in which the capture, transmission, and reception of an image is localized within a closed circuit. This is different than other broadcast images, such as over-the-air television, which is broadcast over the air to any receiver within range. At a minimum, a CCTV system consists of

- One or more cameras
- A monitor for viewing the images
- A system for transmitting the images from the camera to the monitor.

Water monitoring DeVices Proper security preparation really comes down to a three-legged approach: detect, delay, respond. The first leg of security—detect—is discussed in this section; specifically, this section deals with the monitoring of water samples to detect toxicity or contamination. Many of the major monitoring tools that can be used to identify anomalies in process streams or finished water that may represent potential threats are discussed, including

- Sensors to monitor chemical, biological, and radiological contamination
- Arsenic measurement systems
- Biochemical oxygen demand (BOD) analyzers
- Total organic carbon analyzers
- Chlorine measurement systems
- Portable cyanide analyzers
- Portable field monitors to measure volatile organic chemicals

(VOCs) • Radiation detection equipment • Radiation detection equipment for monitoring water assets • Toxicity monitoring and toxicity meters

communication and integration This section discusses those devices that are necessary for communication and the integration of water and wastewater system operations, such as electronic controllers, two-way radios, and wireless data communications. Electronic controllers are used to automatically activate security equipment (such as lights, surveillance cameras, audible alarms, or locks) when they are triggered. Triggering could be the result of the tripping of an alarm or a motion sensor, a window or glass door breaking, variation in vibration sensor readings, or simply input from a timer. Two-way wireless radios allow two or more users who have their radios tuned to the same frequency to communicate instantaneously with each other without the radios being physically connected with wires or cables. Wireless data communications devices are used to enable transmission of data between computer systems or between a SCADA server and its sensing devices, without the individual components being physically linked together via wires or cables. In water and wastewater utilities, these devices are often used to link remote monitoring stations (e.g., SCADA components) or portable computers to computer networks without the use of physical wiring connections.

Electronic Controllers An electronic controller is a piece of electronic equipment that receives incoming electric signals and uses preprogrammed logic to generate electronic output signals based on the incoming signals. Electronic controllers can be implemented for any application that involves inputs and outputs (such as to control equipment in a factory), but in a security application such controllers essentially act as the system's brain and can respond to specific security-related inputs with preprogrammed output responses. These systems combine the control of electronic circuitry with a logic function such that circuits are opened and closed (and equipment is turned on and off) through some preprogrammed logic. The basic principle behind the operation of an electrical controller is that it receives electronic inputs from sensors or any device generating an electrical signal (e.g., electrical signals from motion sensors) and then uses its preprogrammed logic to produce electrical outputs (e.g., these outputs could turn on power to a surveillance camera or an audible alarm). Thus, these systems automatically generate a preprogrammed, logical response to a preprogrammed input scenario. The three major types of electronic controllers are timers, electromechanical relays, and programmable logic controllers (PLCs), which are often called digital relays. Timers use internal signals or inputs (in contrast to externally generated inputs) to generate electronic output signals at certain times. More specifically, timers control electric current flow to any application to which they are connected and can turn the current on or off on a schedule prespecified by the user. Typical timer range (amount of time that can be programmed to elapse before the timer activates linked equipment) is from 0.2 seconds to 10 hours, although some of the more advanced timers have ranges of up to 60 hours. Timers are useful in fixed applications that do not require frequent schedule changes; for example, a timer can be used to turn on the lights in a room or a building at a certain time every day. Timers are usually connected to their own power supply (usually 120 to 240 V). In contrast to timers, which have internal triggers operating on a regular schedule, electromechanical relays and PLCs have both external inputs and external outputs; however, PLCs are more flexible and more powerful than electromechanical relays and are the predominant technology for security-related electronic control applications. Electromechanical relays are simple devices that use a magnetic field to control a switch. Voltage applied to the input coil of the relay creates a magnetic field that attracts an internal metal switch. This causes

the contacts of the relay to touch, thus closing the switch and completing the electrical circuit. This activates any linked equipment. These types of systems are often used for high-voltage applications, such as in some automotive and other manufacturing processes.

Two-Way Radios Two-way radios, as discussed here, are limited to direct unit-to-unit radio communication, either via single unit-to-unit transmission and reception or via multiple handheld units to a base station radio contact and distribution system. Radiofrequency spectrum limitations apply to all hand-held units and are directed by the Federal Communications Commission (FCC). This discussion also distinguishes between a hand-held unit and a base station or base station unit, such as those used by amateur (ham) radio operators, which operate under different wavelength parameters. Two-way radios allow a user to contact another user or group of users instantly on the same frequency and to transmit voice or data without the need for wires. They use half-duplex communication, which means that they cannot transmit and receive data simultaneously. In other words, only one person can talk while other personnel with radios can only listen. To talk, the user depresses the talk button and speaks into the radio. The audio then transmits the voice wirelessly to the receiving radios. When the speaker has finished speaking and the channel has cleared, users on any of the receiving radios can transmit, either to answer the first transmission or to begin a new conversation. In addition to carrying voice data, many types of wireless radios also allow the transmission of digital data, and these radios may be interfaced with computer networks that can use or track these data. Some two-way radios can send information such as global positioning system (GPS) data or the ID of the radio, and others can send data through a SCADA system. Wireless radios broadcast these voice or data communications over the airwaves from the transmitter to the receiver. This can be an advantage in that the signal emanates in all directions and does not require a direct physical connection to be received at the receiver, but it can also make the communications vulnerable to being blocked, intercepted, or otherwise altered. Additional security features are available, however, to ensure that the communications are not tampered with.

Wireless Data Communications A wireless data communication system consists of two components—a wireless access point (WAP) and a wireless network interface card (sometimes also referred to as a client)—which work together to complete the communications link. These wireless systems can link electronic devices, computers, and computer systems together using radiowaves, thus eliminating the need for the individual components to be connected physically via wires. Wireless data communications have found widespread application in water and wastewater systems, but they also have limitations. First, wireless data connections are limited by the distance between components (radiowaves scatter over a long distance and cannot be received efficiently, unless directional antennas are used). Second, these devices only function if the individual components are in direct line of sight with each other, because radiowaves are affected by interference from physical obstructions. In some cases, however, repeater units can be used to amplify and retransmit wireless signals to circumvent these problems. The two components of wireless devices are discussed in more detail below. The wireless access point (WAP) provides the wireless data communication service. It usually consists of a housing (constructed from plastic or metal, depending on the environment in which it will be used) that contains a circuit board, as well as flash memory that holds the necessary software, one of two external ports to connect to existing wired networks, a wireless radio transmitter/receiver, and one or more antenna connections. Typically, the WAP requires a one-time user configuration to allow the device to interact with the local area network (LAN). This configuration is usually accomplished using web-driven software ac-

cessed via a computer. The wireless network interface card or client is a piece of hardware that is plugged into a computer and enables that computer to make a wireless network connection. The card consists of a transmitter, functional circuitry, and a receiver for the wireless signal, all of which work together to enable communication between the computer, its wireless transmitter/receiver, and its antenna connection. Wireless cards are installed in a computer through a variety of connections, including USB adapters or laptop PCMCIA Cardbus or desktop PCI peripheral cards. As for the WAP, software is loaded onto the user's computer, allowing configuration of the card so it may operate over the wireless network. Two of the primary applications for wireless data communications systems are to enable mobile or remote connections to a LAN and to establish wireless communications links between SCADA remote terminal units (RTUs) and sensors in the field. Wireless card connections are usually used for LAN access from mobile computers. Wireless cards can also be incorporated into RTUs to allow them to communicate with sensing devices that are located remotely.

cyber protection DeVices Various cyber protection devices are currently available for use in protecting utility computer systems. These protection devices include antivirus and pest eradication software, firewalls, and network intrusion hardware/software. These products are discussed in this section.

Antivirus and Pest Eradication Software Antivirus programs are designed to detect, delay, and respond to programs or pieces of code that are specifically designed to harm computers. These programs are known as malware. Malware can include computer viruses, worms, and Trojan horse programs (programs that appear to be benign but which have hidden harmful effects). Pest eradication tools are designed to detect, delay, and respond to spyware (strategies that websites use to track user behavior, such as by sending cookies to the user's computer) and hacker tools that track keystrokes (keystroke loggers) or reveal passwords (password crackers). Viruses and pests can enter a computer system through the Internet or through infected CDs or flash drives. They can also be placed onto a system by insiders. Some of these programs, such as viruses and worms, then move throughout the drives and files of a computer or among networked computers. This malware can deliberately damage files, utilize memory and network capacity, crash application programs, and initiate transmissions of sensitive information from a PC. The specific mechanisms of these programs differ, but they all can infect files and affect even the basic operating program of the computer. The most important features of an antivirus program are its abilities to identify potential malware and to alert a user before infection occurs, as well as its ability to respond to a virus already resident on a system. Most of these programs provide a log so the user can see what viruses have been detected and where they were detected. After detecting a virus, the antivirus software may delete the virus automatically, or it may prompt the user to delete the virus. Some programs will also fix files or programs damaged by the virus. Various sources of information are available to inform the general public and computer system operators about new viruses being detected. Because antivirus programs use signatures (or snippets of code or data) to detect the presence of a virus, periodic updates are required to identify new threats. Many antivirus software providers offer free updates that are able to detect and respond to the latest viruses.

Firewalls A firewall is an electronic barrier designed to keep computer hackers, intruders, or insiders from accessing specific data files and information on a utility's computer network or other electronic/computer systems. Firewalls operate by evaluating and then filtering information coming through a public network (such as the Internet) into the utility's computer or other electronic system. This evaluation can include identifying the source or destination addresses and ports and allowing or denying access based on this

identification. Two methods are used by firewalls to limit access to a utility's computers or other electronic systems from the public network:

- The firewall may deny all traffic unless it meets certain criteria.
- The firewall may allow all traffic through unless it meets certain criteria.

A simple example of the first method is screening requests to ensure that they come from an acceptable (i.e., previously identified) domain name and Internet protocol address. Firewalls may also use more complex rules that analyze the application data to determine if the traffic should be allowed through; for example, the firewall may require user authentication (i.e., use of a password) to access the system. How a firewall determines what traffic to let through depends on which network layer it operates within and how it is configured. Firewalls may be a piece of hardware, a software program, or an application card that contains both. Advanced features that can be incorporated into firewalls allow for the tracking of attempts to log onto the local area network system; for example, a report of successful and unsuccessful log-in attempts may be generated for the computer specialist to analyze. For systems with mobile users, firewalls allow remote access to the private network via secure log-on procedures and authentication certificates. Most firewalls have a graphical user interface for managing the firewall. In addition, Ethernet firewall cards that fit in the slots of individual computers bundle additional layers of defense (such as encryption and permit/deny) for individual computer transmissions to the network interface function. The cost of these cards is only slightly higher than for traditional network interface cards.

Network Intrusion Hardware/Software Network intrusion detection and prevention systems are software and hardware based programs designed to detect unauthorized attacks on a computer network system. Whereas other applications, such as firewalls and antivirus software, share similar objectives with network intrusion systems, network intrusion systems provide a deeper layer of protection beyond the capabilities of these other systems because they evaluate patterns of computer activity rather than specific files. It is worth noting that attacks may come from either outside or within the system (i.e., from an insider) and that network intrusion detection systems may be more applicable for detecting patterns of suspicious activity from inside a facility (e.g., accessing sensitive data) than other information technology solutions. Network intrusion detection systems employ a variety of mechanisms to evaluate potential threats. The types of search and detection mechanisms are dependent upon the level of sophistication of the system. Some of the available detection methods include the following:

- **Protocol analysis**—Protocol analysis is the process of capturing, decoding, and interpreting electronic traffic. The protocol analysis method of network intrusion detection involves the analysis of data captured during transactions between two or more systems or devices and the evaluation of these data to identify unusual activity and potential problems. When a problem has been isolated and recorded, potential threats can be linked to pieces of hardware or software. Sophisticated protocol analysis will also provide statistics and trend information on the captured traffic.
- **Traffic anomaly detection**—Traffic anomaly detection identifies potential threatening activity by comparing incoming traffic to normal traffic patterns and identifying deviations. It does this by comparing user characteristics against thresholds and triggers defined by the network administrator. This method is designed to detect attacks that span a number of connections, rather than a single session.
- **Network honeypot**—This method establishes nonexistent services to identify potential hackers. A network honeypot impersonates services that do not exist by sending fake information to people scanning the network. It identifies attackers when they attempt to connect

to the service. There is no reason for legitimate traffic to access these resources because they do not exist; therefore, any attempt to access them constitutes an attack. • Anti-intrusion detection system evasion techniques—These methods are designed to detect attackers who may be trying to evade intrusion detection system scanning. They include such methods as IP defragmentation, TCP streams reassembly, and deobfuscation.

These detection systems are automated, but they can only indicate patterns of activity, and a computer administrator or other experienced individual must interpret the activities to determine whether or not they are potentially harmful. Monitoring the logs generated by these systems can be time consuming, and there may be a learning curve to determine a baseline of normal traffic patterns from which to distinguish potential suspicious activity.

SCADA

The Federal Bureau of Investigation (FBI) identified and listed threats to critical infrastructure (see Table 12.1). In the past few years, especially since 9/11, it has been somewhat routine for us to pick up a newspaper or magazine or to view a television news program where a major topic of discussion is cyber security or the lack

thereof. Many of the cyber intrusion incidents we read or hear about have added new terms or new uses for old terms to our vocabulary; for example, old terms such as Trojan horse, worms, and viruses have taken on new connotations with regard to cyber security issues. Relatively new terms such as scanners, hacking, mail bombs, sniffers, logic bombs, nukers, dots, backdoor Trojan, key loggers, Swiss Army knife of hacking, password crackers, and BIOS crackers are now commonly encountered. Not all relatively new and universally recognizable cyber terms have sinister connotation or meaning, of course. Consider, for example, the following digital terms: app, avatar, backup, binary, bit, byte, cloaking, CPU, cyberspace, database, email, HTML, icon, IM, memory, monitor, network, RAM, thumb drive, Wi-Fi, World Wide Web—none of these terms normally generates thoughts of terrorism in most of us. There is, however, one digital term, SCADA, that most people have not heard

of. This is not the case, however, for those who work with the nation's critical infrastructure, including water/wastewater. SCADA, an acronym for supervisory control and data acquisition and sometimes referred to as digital control systems or process control systems, plays an important role in computer-based control systems. Many water/wastewater systems use computer-based systems to remotely control sensitive processes and system equipment previously controlled manually. These SCADA systems allow a water/wastewater utility to collect data from sensors and control equipment located at remote sites. Common water/wastewater system sensors measure elements such as fluid level, temperature, pressure, water purity, water clarity, and pipeline flow rates. Common water/wastewater system equipment includes valves, pumps, and mixers for mixing chemicals in the water supply.

What is scaDa? Simply, SCADA is a computer-based system that remotely controls processes previously controlled manually. SCADA allows an operator using a central computer to supervise (control and monitor) multiple networked computers at remote locations. Each remote computer can control mechanical processes (pumps, valves, etc.) and collect data from sensors at its remote location, thus the phrase supervisory control and data acquisition, or SCADA. The central computer is the master terminal unit (MTU). The operator interfaces with the MTU using software known as the human-machine interface (HMI). The remote computer is the programmable logic controller (PLC) or remote terminal unit (RTU). The

RTU activates a relay (or switch) that turns mechanical equipment on and off. The RTU also collects data from sensors. In the initial stages, utilities ran wires (hardwire or land lines) from the central computer (MTU) to the remote computers (RTUs). Because remote locations can be located hundreds of miles from the central location, utilities began to use public phone lines and modems, leased telephone company lines, and radio and microwave communication. Today, they are also using satellite links, the Internet, and newly developed wireless technologies. Because the sensors of SCADA systems provide valuable information, many utilities established connections between their SCADA system and their business system. This allowed utility management and other staff access to valuable statistics, such as water usage. When utilities later connected their systems to the Internet, they were able to provide stakeholders with water/wastewater statistics on the utility's web pages.

scaDa applications in Water systems As stated above, SCADA systems can be designed to monitor a variety of equipment operating conditions and parameters, such as volumes, flow rates, or water quality, as well as to respond to changes in those parameters either by alerting operators or by modifying system operation through a feedback loop system without having personnel physically visit each process or piece of equipment on a daily basis to check it to ensure that it is functioning properly. SCADA systems can also be used to automate certain functions, so they can be performed without having to be initiated by an operator (e.g., injecting chlorine in response to periodic low chlorine levels in a distribution system or turning on a pump in response to low water levels in a storage tank). In addition to process equipment, SCADA systems can also integrate specific security alarms and equipment, such as cameras, motion sensors, lights, data from card-reading systems, etc., thereby providing a clear picture of what is happening at areas throughout a facility. Finally, SCADA systems also provide constant, real-time data on processes, equipment, location access, etc., so the necessary response can be made quickly. This can be extremely useful during emergency conditions, such as when distribution mains break or when potentially disruptive BOD spikes appear in wastewater influent. Because these systems can monitor multiple processes, equipment, and infrastructure and then provide quick notification of or response to problems or disruptions, SCADA systems typically provide the first line of detection for atypical or abnormal conditions. For example, a real-time, customized operator interface screen can display critical system monitoring parameters, while a SCADA system connected to sensors that measure the water quality parameters can report findings measured outside of a specific range. The system can transmit warning signals back to the operators, such as by initiating a call to a personal pager. This might allow the operators to initiate actions to prevent contamination and disruption of the water supply. Further automation of the system could ensure that the system initiates measures to rectify the problem. Preprogrammed control functions (e.g., shutting a valve, controlling flow, increasing chlorination, or adding other chemicals) can be triggered and operated based on SCADA utility.

scaDa Vulnerabilities SCADA networks were developed with little attention paid to security, thus the security of these systems can often be weak. Studies have found that, although technological advancements introduced vulnerabilities, many water/wastewater utilities have spent little time securing their SCADA networks, many of which may be susceptible to attacks and misuse. Remote monitoring and supervisory control of processes were initially developed in the early 1960s and have since adopted many technological advancements. The advent of minicomputers made it possible to automate a vast number of once manually operated switches. Advancements in radio technology reduced the communication costs associated

with installing and maintaining buried cable in remote areas. SCADA systems continued to adopt new communication methods, including satellite and cellular. As the price of computers and communications dropped, it became economically feasible to distribute operations and to expand SCADA networks to include even smaller facilities (USEPA, 2005). Advances in information technology and the necessity of improved efficiency have resulted in increasingly automated and interlinked infrastructures and created new vulnerabilities due to equipment failure, human error, weather and other natural causes, and physical and cyber attacks. Some examples of possible SCADA vulnerabilities include the following:

- Humans—People can be tricked or corrupted and may commit errors.
- Communications—Messages can be fabricated, intercepted, changed, deleted, or blocked.
- Hardware—Security features are not easily adapted to small self-contained units with limited power supplies.
- Physical threats—Intruders can break into a facility to steal or damage SCADA equipment.
- Natural threats—Tornadoes, floods, earthquakes, and other natural disasters can damage equipment and connections.
- Software—Programs can be poorly written.

An early survey among water utilities found that they were doing little to secure their SCADA network vulnerabilities (Ezell, 1998); for example, many respondents reported that they had remote access, which can allow an unauthorized person to access the system without being physically present. More than 60% of the respondents believed that their systems were not safe from unauthorized access and use, and 20% of the respondents reported known attempts and successful unauthorized access to their systems. Yet, 22 of 43 respondents reported that they did not spend any time ensuring the safety of their networks, and 18 of 43 respondents reported that they spent less than 10% of their time ensuring network safety. SCADA system computers and their connections are susceptible to a variety of information system attacks and misuse, such as system penetration and unauthorized access to information. The Computer Security Institute has conducted annual computer crime and security surveys. A recent survey reported that malware and phishing were the attacks experienced by respondents most often (CSI, 2011). The study also found that 7% of the respondents reported exploited wireless networks, components of a SCADA system. That number is down, however, from a reported 16% in 2005. On average, respondents from all sectors did not believe that their organization invested enough in security awareness. Utilities as a group reported a lower average computer security expenditure/investment per employee than many other sectors such as transportation, telecommunications, and financial. Sandia National Laboratories categorized common problems it has identified in the following five categories (Stamp et al., 2003):

1. System data—Important data attributes for security include availability, authenticity, integrity, and confidentiality. Data should be categorized according to their sensitivity, and ownership and responsibility must be assigned; however, SCADA data are often not classified at all, making it difficult to identify where security precautions are appropriate.
2. Security administration—Vulnerabilities emerge because many systems lack a properly structured security policy, equipment and system implementation guides, configuration management, training, and enforcement and compliance auditing.
3. Architecture—Many common practices negatively affect SCADA security; for example, although it is convenient to use SCADA capabilities for other purposes such as fire and security systems, these

practices create single points of failure. Also, the connection of SCADA networks to other automation systems and business networks introduces multiple entry points for potential adversaries.

4. Network (including communication links)—Legacy system hardware and software have very limited security capabilities, and the vulnerabilities of contemporary systems (based on modern information technology) are publicized. Wireless and shared links are susceptible to eavesdropping and data manipulation.
5. Platforms—Many platform vulnerabilities exist, including default configurations still in place, poor password practices, shared accounts, inadequate protection for hardware, and nonexistent security monitoring controls. In most cases, important security patches are not installed, often due to concern about negatively impacting system operation; in some cases, technicians are contractually forbidden from updating systems by their vendor agreements.

The following incident helps to illustrate some of the risks associated with SCADA vulnerabilities (USEPA, 2005):

During the course of conducting a vulnerability assessment, a contractor stated that personnel from his company penetrated the information system of a utility within minutes. Contractor personnel drove to a remote substation and noticed a wireless network antenna. Without leaving their vehicle, they plugged in their wireless radios and connected to the network within 5 minutes. Within 20 minutes they had mapped the network, including SCADA equipment, and accessed the business network and data.

INCREASING RISK Historically, security concerns about control systems (SCADA included) were related primarily to protecting against physical attack and misuse of refining and processing sites or distribution and holding facilities (GAO, 2003). More recently, however, there has been a growing recognition that control systems are now vulnerable to cyber attacks from numerous sources, including hostile governments, terrorist groups, disgruntled employees, and other malicious intruders. In addition to control system vulnerabilities mentioned earlier, several factors have contributed to the escalation of risk to control systems: (1) the adoption of standardized technologies with known vulnerabilities, (2) the connectivity of control systems to other networks, (3) constraints on the implementation of existing security technologies and practices, (4) insecure remote connections, and (5) the widespread availability of technical information about control systems.

Adoption of technologies With known Vulnerabilities When a technology is not well known, not widely used, not understood, or not publicized, it is difficult to penetrate it and thus disable it. Historically, proprietary hardware, software, and network protocols made it difficult to understand how control systems operated—and therefore how to hack into them. Today, however, to reduce costs and improve performance, organizations have been transitioning from proprietary systems to less expensive, standardized technologies such as Microsoft's Windows and Unix-like operating systems and the common networking protocols used by the Internet. These widely used standardized technologies have commonly known vulnerabilities, and sophisticated and effective exploitation tools are widely available and relatively easy to use. As a consequence, both the number of people with the knowledge to wage attacks and the number of systems subject to attack have increased. Also, common communication protocols and the use of Extensible Markup Language (XML) can make it easier for a hacker to interpret the content of communications

among the components of a control system. Control systems are often connected to other networks, as enterprises often integrate their control systems with their enterprise networks. This increased connectivity has significant advantages, including providing decision makers with access to realtime information and allowing engineers to monitor and control the process control system from different points on the enterprise network. In addition, the enterprise networks are often connected to the networks of strategic partners and to the Internet. Further, control systems are increasingly using wide area networks and the Internet to transmit data to their remote or local stations and individual devices. This convergence of control networks with public and enterprise networks potentially exposes the control systems to additional security vulnerabilities. Unless appropriate security controls are deployed in the enterprise network and the control system network, breaches in enterprise security can affect the operation of controls system. According to industry experts, the use of existing security technologies, as well as strong user authentication and patch management practices, are generally not implemented in control systems because control systems operate in real time, typically are not designed with cyber security in mind, and usually have limited processing capabilities. Existing security technologies such as authorization, authentication, encryption, intrusion detection, and filtering of network traffic and communications require more bandwidth, processing power, and memory than control system components typically have. Because controller stations are generally designed to do specific tasks, they use low-cost, resource-constrained microprocessors. In fact, some devices in the electrical industry still use the Intel 8088 processor first introduced in 1978; consequently, it is difficult to install existing security technologies without seriously degrading the performance of the control system. Further, complex passwords and other strong password practices are not always used to prevent unauthorized access to control systems, in part because this could hinder a rapid response to safety procedures during an emergency. As a result, according to experts, weak passwords that are easy to guess, shared, and infrequently changed are reportedly common in control systems, as well as the use of default passwords or even no password at all. In addition, although modern control systems are based on standard operating systems, they are typically customized to support control system applications; consequently, vendor-provided software patches are generally either incompatible or cannot be implemented without compromising service by shutting down always-on systems or affecting interdependent operations. Insecure connections exacerbate potential vulnerabilities. Organizations often leave access links open for remote diagnostics, maintenance, and examination of system status. Such links may not be protected with authentication or encryption which increases the risk that hackers could use these insecure connections to break into remotely controlled systems. Also, control systems often use wireless communications systems, which are especially vulnerable to attack, or leased lines that pass through commercial telecommunications facilities. Without encryption to protect data as it flows through these insecure connections or authentication mechanisms to limit access, there is limited protection for the integrity of the information being transmitted. Public information about infrastructures and control systems is available to potential hackers and intruders. The relatively easy availability of such data was demonstrated by a university graduate student whose dissertation reportedly mapped every business and industrial sector in the American economy to the fiberoptic network that connects them—using material that was available publicly on the Internet, none of which was classified. Many of the electric utility officials who were interviewed for the National Security Telecommunications Advisory Committee's Information Assurance Task Force's Electric Power Risk Assessment expressed concern over the amount of information about their infrastructure that

is readily available to the public. In the electric power industry, open sources of information, such as product data and educational videotapes from engineering associations, can be used to understand the basics of the electrical grid. Other publicly available information, including filings of the Federal Energy Regulatory Commission (FERC), industry publications, maps, and material available on the Internet, is sufficient to allow someone to identify the most heavily loaded transmission lines and the most critical substations in the power grid. Significant information on control systems is publicly available, including design and maintenance documents, technical standards for the interconnection of control systems and remote terminal units, and standards for communication among control devices—all of which could assist hackers in determining how to attack them. Moreover, numerous former employees, vendors, support contractors, and other end users of the same equipment worldwide have inside knowledge of the operation of control systems.

cyber threats to control systems There is a general consensus—and increasing concern—among government officials and experts on control systems regarding potential cyber threats to the control systems that govern our critical infrastructures. As components of control systems increasingly make critical decisions that were once made by humans, the potential effect of a cyber threat becomes more devastating. Such cyber threats could come from numerous sources, ranging from hostile governments and terrorist groups to disgruntled employees and other malicious intruders. Based on interviews and discussions with representatives throughout the electric power industry, the Information Assurance Task Force of the National Security Telecommunications Advisory Committee concluded that an organization with sufficient resources, such as a foreign intelligence service or a well-supported terrorist group, could conduct a structured attack on the electric power grid electronically, with a high degree of anonymity and without having to set foot in the target nation. The National Infrastructure Protection Center (NIPC, 2002) reported that the potential for compound cyber and physical attacks, referred to as swarming attacks, is a significant threat to the U.S. critical infrastructure. The effects of a swarming

attack include slowing or complicating any response to the physical attack. An example would be a cyber attack that disabled the water supply or the electrical system in conjunction with a physical attack that denied emergency services the resources necessary to manage the consequences, such as controlling fires, coordinating actions, and generating light. Control systems, such as SCADA, can be vulnerable to cyber attacks. Entities or individuals with malicious intent might take one or more of the following actions to successfully attack control systems:

- Disrupt the operation of control systems by delaying or blocking the flow of information through control networks, thereby denying availability of the networks to control system operations.
- Make unauthorized changes to programmed instructions in PLCs, RTUs, or distributed control system (DCS) controllers; change alarm thresholds; or issue unauthorized commands to control equipment, which could potentially result in damage to equipment (if tolerances are exceeded), premature shutdown of processes (such as prematurely shutting down transmission lines), or even disabling control equipment.
- Send false information to control system operators either to disguise unauthorized changes or to initiate inappropriate actions by system operators.
- Modify control system software, producing unpredictable results.
- Interfere with the operation of safety systems.

Also, in control systems that cover a wide geographic area, the remote sites are often unstaffed and may not be physically monitored. If such remote systems are physically breached, the attackers could establish

a cyber connection to the control network.

securing control systems Several challenges must be addressed to effectively secure control systems against cyber threats. These challenges include: (1) limitations of current security technologies with regard to securing control systems, (2) the perception that securing control systems may not be economically justifiable, and (3) conflicting priorities within organizations regarding the security of control systems. A significant challenge in effectively securing control systems is the lack of specialized security technologies for these systems. The computing resources in control systems that are required to perform security functions tend to be quite limited, making it very difficult to use security technologies within control system networks without severely hindering performance. Securing control systems may not be perceived as economically justifiable. Experts and industry representatives have indicated that organizations may be reluctant to spend more money to secure control systems. Hardening the security of control systems would require industries to expend more resources, including acquiring more personnel, providing training for personnel, and potentially prematurely replacing current systems that typically have a lifespan of about 20 years. Finally, several experts and industry representatives have indicated that the responsibility for securing control systems typically includes two separate groups: IT security personnel

and control system engineers and operators. IT security personnel tend to focus on securing enterprise systems, while control system engineers and operators tend to be more concerned with the reliable performance of their control systems. Further, they indicate that, as a result, those two groups do not always fully understand each other's requirements and do not collaborate to implement secure control systems.

steps to improve SCADA security The President's Critical Infrastructure Protection Board and the Department of Energy (DOE) developed the steps outlined below to help organizations improve the security of their SCADA networks. These steps are not meant to be prescriptive or all inclusive; however, they do address essential actions to be taken to improve the protection of SCADA networks. The steps are divided into two categories: specific actions to improve implementation and actions to establish essential underlying management processes and policies (DOE, 2001).

21 Steps to Increase SCADA Security The following steps focus on specific actions to be taken to increase the security of SCADA networks (DOE, 2001):

1. Identify all connections to SCADA networks. Conduct a thorough risk analysis to assess the risk and necessity of each connection to the SCADA network. Develop a comprehensive understanding of all connections to the SCADA network and how well those connections are protected. Identify and evaluate the following types of connections:
 - Internal local area and wide area networks, including business networks
 - The Internet
 - Wireless network devices, including satellite uplinks
 - Modem or dial-up connections
 - Connections to business partners, vendors, or regulatory agencies
2. Disconnect unnecessary connections to the SCADA network. To ensure the highest degree of security of SCADA systems, isolate the SCADA network from other network connections to as great a degree as possible. Any connection to another network introduces security risks, particularly if the connection creates a pathway from or to the Internet. Although direct connections with other networks may allow important information to be passed efficiently and conveniently, insecure connections are simply not worth the risk; isolation of the SCADA network must be a primary goal to provide needed protection. Strategies such as the utilization of demilitarized zones (DMZs) and data

warehousing can facilitate the secure transfer of data from the SCADA network to business networks; however, they must be designed and implemented properly to avoid the introduction of additional risk through improper configuration.

3. Evaluate and strengthen the security of any remaining connections to the SCADA networks. Conduct penetration testing or vulnerability analysis of any remaining connections to the SCADA network to evaluate the

protection posture associated with these pathways. Use this information in conjunction with risk-management processes to develop a robust protection strategy for any pathways to the SCADA network. Because the SCADA network is only as secure as its weakest connecting point, it is essential to implement firewalls, intrusion detection systems (IDSs), and other appropriate security measures at each point of entry. Configure firewall rules to prohibit access from and to the SCADA network, and be as specific as possible when permitting approved connections. For example, an Independent System Operator (ISO) should not be granted blanket network access simply because of a need for a connection to certain components of the SCADA system. Strategically place IDSs at each entry point to alert security personnel of potential breaches of network security. Organization management must understand and accept responsibility or risks associated with any connection to the SCADA network.

4. Harden SCADA networks by removing or disabling unnecessary services. SCADA control servers built on commercial or open-source operating systems can be exposed to attack through default network services. To the greatest degree possible, remove or disable unused services and network demons to reduce the risk of direct attack. This is particularly important when SCADA networks are interconnected with other networks. Do not permit a service or feature on a SCADA network unless a thorough risk assessment of the consequences of allowing the service or feature shows that the benefits of the service or feature far outweigh the potential for vulnerability exploitation. Examples of services to remove from SCADA networks include automated meter reading/remote billing systems, e-mail services, and Internet access. An example of a feature to disable is remote maintenance. Refer to the National Security Agency's series of security guides. Additionally, work closely with SCADA vendors to identify secure configurations and coordinate any and all changes to operational systems to ensure that removing or disabling services does not cause downtime, interruption of service, or loss of support.
5. Do not rely on proprietary protocols to protect your system. Some SCADA systems are unique, proprietary protocols for communications between field devices and servers. Often the security of SCADA systems is based solely on the secrecy of these protocols. Unfortunately, obscure protocols provide very little real security. Do not rely on proprietary protocols or factor default configuration settings to protect your system. Additionally, demand that vendors disclose any backdoors or vendor interfaces to your SCADA systems, and expect them to provide systems that are capable of being secured.
6. Implement the security features provided by device and system vendors. Older SCADA systems (most systems in use) have no security features whatsoever. SCADA system owners must insist that their system vendors implement security features in the form of product patches or upgrades. Some newer SCADA devices are shipped with basic security features, but these are usually disabled to ensure ease of installation. Analyze each SCADA

device to determine whether security features are present. Additionally, factory default security settings (such as in computer network firewalls) are often set to provide maximum usability but minimal secu-

rity. Set all security features to provide the maximum security only after a thorough risk assessment of the consequences of reducing the security level. 7. Establish strong controls over any medium that is used as a backdoor into the SCADA network. Where backdoors or vendor connections do exist in SCADA systems, strong authentication must be implemented to ensure secure communications. Modems, wireless, and wired networks used for communications and maintenance represent a significant vulnerability to the SCADA network and remote sites. Successful “war dialing” or “war driving” attacks could allow an attacker to bypass all of other controls and have direct access to the SCADA network or resources. To minimize the risk of such attacks, disable inbound access and replace it with some type of callback system. 8. Implement internal and external intrusion detection systems and establish 24-hour-a-day incident monitoring. To be able to effectively respond to cyber attacks, establish an intrusion detection strategy that includes alerting network administrators of malicious network activity originating from internal or external sources. Intrusion detection system monitoring is essential 24 hours a day; this capability can be easily set up through a pager. Additionally, incident response procedures must be in place to allow an effective response to any attack. To complement network monitoring, enable logging on all systems and audit system logs daily to detect suspicious activity as soon as possible. 9. Perform technical audits of SCADA devices and networks, and any other connected networks, to identify security concerns. Technical audits of SCADA devices and networks are critical to ongoing security effectiveness. Many commercial and open-sourced security tools are available that allow system administrators to conduct audits of their systems and networks to identify active services, patch level, and common vulnerabilities. The use of these tools will not solve systemic problems but will eliminate the paths of least resistance that an attacker could exploit. Analyze identified vulnerabilities to determine their significance, and take corrective actions as appropriate. Track corrective actions and analyze this information to identify trends. Additionally, retest systems after corrective actions have been taken to ensure that vulnerabilities were actually eliminated. Scan nonproduction environments actively to identify and address potential problems. 10. Conduct physical security surveys and assess all remote sites connected to the SCADA network to evaluate their security. Any location that has a connection to the SCADA network is a target, especially unmanned or unguarded remote sites. Conduct a physical security survey and inventory access points at each facility that has a connection to the SCADA system. Identify and assess any source of information, including remote telephone/ computer network/fiberoptic cables, that could be tapped; radio and microwave links that are exploitable; computer terminals that could be accessed; and wireless local area network access points. Identify and eliminate single points of failure. The security of the site must be adequate to detect or prevent unauthorized access. Do not allow live network access points at remote, unguarded sites simply for convenience. 11. Establish SCADA “Red Teams” to identify and evaluate possible attack scenarios. Establish a “Red Team” to identify potential attack scenarios and evaluate potential system vulnerabilities. Use a variety of people who can provide insight into weaknesses of the overall network, SCADA system, physical systems, and security controls. People who work on the system every day have great insight into the vulnerabilities of the SCADA network and should be consulted when identifying potential attack scenarios and possible consequences. Also, ensure that the risk from a malicious insider is fully evaluated, given that this represents one of the greatest threats to an organization. Feed information resulting from the “Red Team” evaluation into risk-management processes to assess the information and establish appropriate protection strategies.

The following steps focus on management actions to establish an effective cyber security program:

1. Clearly define cyber security roles, responsibilities, and authorities for managers, system administrators, and users. Organization personnel need to understand the specific expectations associated with protecting information technology resources through the definition of clear and logical roles and responsibilities. In addition, key personnel need to be given sufficient authority to carry out their assigned responsibilities. Too often, good cyber security is left up to the initiative of the individual, which usually leads to inconsistent implementations and ineffective security. Establish a cyber security organizational structure that defines roles and responsibilities and clearly identifies how cyber security issues are escalated and who is notified in an emergency.
2. Document network architecture and identify systems that serve critical functions or contain sensitive information that require additional levels of protection. Develop and document a robust information security architecture as part of a process to establish an effective protection strategy. It is essential that organizations design their network with security in mind and continue to have a strong understanding of their network architecture throughout its lifecycle. Of particular importance, an in-depth understanding of the functions that the systems perform and the sensitivity of the stored information is required. Without this understanding, risk cannot be properly assessed and protection strategies may not be sufficient. Documenting the information security architecture and its components is critical to understanding the overall protection strategy and identifying single points of failure.
3. Establish a rigorous, ongoing risk-management process. A thorough understanding of the risks to network computing resources from denial-of-service attacks and the vulnerability of sensitive information to compromise is

essential to an effective cyber security program. Risk assessments form the technical basis of this understanding and are critical to formulating effective strategies to mitigate vulnerabilities and preserve the integrity of computing resources. Initially, perform a baseline risk analysis based on current threat assessment to use for developing a network protection strategy. Due to rapidly changing technology and the emergence of new threats on a daily basis, an ongoing risk-assessment process is also needed so routine changes can be made to the protection strategy to ensure it remains effective. Fundamental to risk management is identification of residual risk with a network protection strategy in place and acceptance of that risk by management. 15. Establish a network protection strategy based on the principle of defense in depth. A fundamental principle that must be part of any network protection strategy is defense in depth. Defense in depth must be considered early in the design phase of the development process and must be an integral consideration in all technical decision-making associated with the network. Utilize technical and administrative controls to mitigate threats from identified risks to as great a degree as possible at all levels of the network. Single points of failure must be avoided, and cyber security defense must be layered to limit and contain the impact of any security incidents. Additionally, each layer must be protected against other systems at the same layer. For example, to protect against the inside threat, restrict users to access only those resources necessary to perform their job functions. 16. Clearly identify cyber security requirements. Organizations and companies need structured security programs with mandated requirements to establish expectations and allow personnel to be held accountable. Formalized policies and procedures

are typically used to establish and institutionalize a cyber security program. A formal program is essential to establishing a consistent, standards-based approach to cyber security through an organization and eliminates sole dependence on individual initiative. Policies and procedures also inform employees of their specific cyber security responsibilities and the consequences of failing to meet those responsibilities. They also provide guidance regarding actions to be taken during a cyber security incident and promote efficient and effective actions during a time of crisis. As part of identifying cyber security requirements, include user agreements and notification and warning banners. Establish requirements to minimize the threat from malicious insiders, including the need for conducting background checks and limiting network privileges to those absolutely necessary. 17. Establish effective configuration management processes. A fundamental management process needed to maintain a secure network is configuration management. Configuration management must cover both hardware configurations and software configurations. Changes to hardware or software can easily introduce vulnerabilities that undermine network security. Processes are required to evaluate and control any change to ensure that the network remains secure. Configuration management begins with well-tested and documented security baselines for your various systems.

1. Conduct routine self-assessments. Robust performance evaluation processes are needed to provide organizations with feedback on the effectiveness of cyber security policy and technical implementation. A sign of a mature organization is one that is able to identify issues, conduct root-cause analyses, and implement effective corrective actions that address individual and systemic problems. Self-assessment processes that are normally part of an effective cyber security program include routine scanning for vulnerabilities, automated auditing of the network, and self-assessments of organizational and individual performance.
2. Establish system backups and disaster recovery plans. Establish a disaster recovery plan that allows for rapid recovery from any emergency (including a cyber attack). System backups are an essential part of any plan and allow rapid reconstruction of the network. Routinely exercise disaster recovery plans to ensure that they work and that personnel are familiar with them. Make appropriate changes to disaster recovery plans based on lessons learned from exercises.
3. Senior organizational leadership should establish expectations for cyber security performance and hold individuals accountable for their performance. Effective cyber security performance requires commitment and leadership from senior managers in the organization. It is essential that senior management establish an expectation for strong cyber security and communicate this to their subordinate managers throughout the organization. It is also essential that senior organizational leadership establish a structure for implementation of a cyber security program. This structure will promote consistent implementation and the ability to sustain a strong cyber security program. It is then important for individuals to be held accountable for their performance as it relates to cyber security. This includes managers, system administrators, technicians, and users/operators.
4. Establish policies and conduct training to minimize the likelihood that organizational personnel will inadvertently disclose sensitive information regarding SCADA system design, operations, or security controls. Release data related to the SCADA network only on a strict, need-to-know basis and only

to persons explicitly authorized to receive such information. “Social engineering,” the gathering of information about a computer or computer network via questions to naïve users, is often the first step in a malicious attack on computer networks. The more information revealed about a computer or network, the more vulnerable the computer or network is. Never divulge data revealed to a SCADA network, including names and contact information about the system operators and administrators, computer operating systems, or physical and logical locations of computers and network systems over the telephone or to personnel unless they are explicitly authorized to receive such information. Any requests for information by unknown persons should be sent to a central network security location for verification and fulfillment. People can be a weak link in an otherwise secure network. Conduct training and information awareness campaigns to ensure that personnel remain diligent in guarding sensitive network information, particularly their passwords.

THE BOTTOM LINE Again, when it comes to the security of our nation and even of water/wastewater treatment facilities, few have summed it up better than Tom Ridge (Henry, 2002):

Now, obviously, the further removed we get from September 11, the natural tendency is to let down our guard. Unfortunately, we cannot do that. . . . The government will continue to do everything we can to find and stop those who seek to harm us. And I believe we owe it to the American people to remind them that they must be vigilant, as well.