

9. Size and understand the operation of water treatment unit processes used for coagulation and flocculation, sedimentation, granular filtration, disinfection, hardness removal by lime-soda softening, and removal of dissolved organic and inorganic chemicals by activated carbon and membrane techniques.
10. Write the chemical equation(s) to describe the application of different disinfectants and differentiate between residual chlorine and the three chemical species that make up combined chlorine.
11. Demonstrate an in-depth understanding of disinfection processes for different disinfectants used in a developed and developing world setting.
12. Differentiate between the different types of membrane filters and the size and type of constituents they are designed to remove.
13. Identify the magnitude of energy use during plant operation for different unit processes while also being aware of energy considerations associated with the life cycle of particular unit processes.

8.1 Introduction

Freshwater is a finite resource, and readily accessible supplies are becoming less abundant. With water scarcity a reality in many parts of the world, increases in population and income along with the impacts of climate change are expected to further exacerbate this issue. Achieving sustainable solutions is compounded by the energy demands of obtaining, storing, and producing a safe water supply. Approximately 1.4 kWh of energy are needed to collect and treat 1,000 gallons of surface water, and 1.8 kWh are needed to collect and treat a similar volume of groundwater (Burton, 1996; Elliot et al., 2003). For water treatment, most of this requirement is from pumping either raw or treated water or some concentrated waste stream. There is, of course, energy associated with manufacturing and delivering materials and chemicals used during pumping and treatment. Therefore, the distances to a water source and its quality could have a large energy implication from a life cycle perspective (Mo et al., 2011).

And as society develops less desirable sources of water to meet increasing demand, the amount of embodied energy in our water supply is expected to increase. Consequently, there is a need to develop an integrated systems approach to water management strategies (for example, sustainable watershed management, water conservation, and water reuse practices) to meet the global demand for safe drinking water. In terms of reuse, approximately 12 billion gallons of municipal effluent is discharged daily to an ocean or estuary (out of 32 billion gallons discharged every day in the United States). Much of this discharge still contains nutrients that harm coastal ecosystems. If society would only reuse these coastal discharges, we could augment 6 percent of the estimated total water use in the United States, which is equivalent to 27 percent of public water supply (NRC, 2012).

The purpose of **water treatment** is to provide potable water that is palatable. **Potable water** refers to water that is healthy for human consumption and free of harmful microorganisms and organic and inorganic compounds that either cause adverse physiological effects or do not taste good. **Palatable** describes water that is *aesthetically* acceptable to drink or free from turbidity, color, odor, and objectionable taste. Water that is palatable may not be safe.

In developed countries, water is treated to be both potable and palatable. However, some people do not like the palatability of municipal waters, and this has given rise to the increased use of household point-of-use treatment systems and bottled water. Bottled water has added an additional layer of embodied energy to water, because petroleum is used to produce the water container, and there are recycling or disposal costs for the bottles during their end-of-life life stage.

Application / 8.1 Global Definitions of Improved Water Supplies

Table / 8.1

Global Definitions of Improved and Unimproved Water Supplies

Improved Water Supplies	Unimproved Water Supplies
Household connections	Unprotected well
Public standpipes	Unprotected spring
Boreholes	Vendor-provided water
Protected dug wells	Bottled water
Protected springs	Tanker truck-provided water
Rainwater collection	

For those working on engineering projects in the developing world, a water supply can be improved with many types of projects and appropriate technology, from protecting a water source to building a distribution system. Table 8.1 describes how the World Health Organization (WHO) defines *unimproved* and *improved water supplies*. Bottled water is considered unimproved because of possible problems of sufficient quantity, not quality).

8.2 Characteristics of Untreated Water

Most consumers expect drinking water to be clear, colorless, odorless, and free of harmful chemicals and pathogenic microorganisms. Natural waters usually contain some degree of dissolved, particulate, and microbiological constituents, which are obtained from the surrounding environment. Table 8.2 summarizes many of the important chemical and biological constituents found in water. Chapter 7 discussed how precipitation and land use impact the quantity and quality of runoff that enters a watershed. Figure 8.1 shows specifically how several

Table / 8.2

Concentration of Major Constituents Found in Water

General Classification	Specific Constituents	Typical Concentration Range
Major inorganic constituents	Calcium (Ca^{2+}), chloride (Cl^-), fluoride (F^-), iron (Fe^{2+}), manganese (Mn^{2+}), nitrate (NO_3^-), sodium (Na^+), sulfur (SO_4^{2-} , HS^-)	1–1,000 mg/L
Minor inorganic constituents	Cadmium, chromium, copper, lead, mercury, nickel, zinc, arsenic	0.1–10 $\mu\text{g/L}$
Naturally occurring organic compounds	Naturally occurring organic matter (NOM) that is measured as total organic carbon (TOC)	0.1–20 mg/L
Anthropogenic organic constituents	Synthetic organic chemicals (SOCs) and emerging chemicals of concern used in industry, households, and agriculture (e.g., benzene, methyl tert-butyl ether, tetrachloroethylene, trichloroethylene, vinyl chloride, alachlor)	Below 1 $\mu\text{g/L}$ and up to the tens of mg/L
Living organisms	Bacteria, algae, viruses	Millions

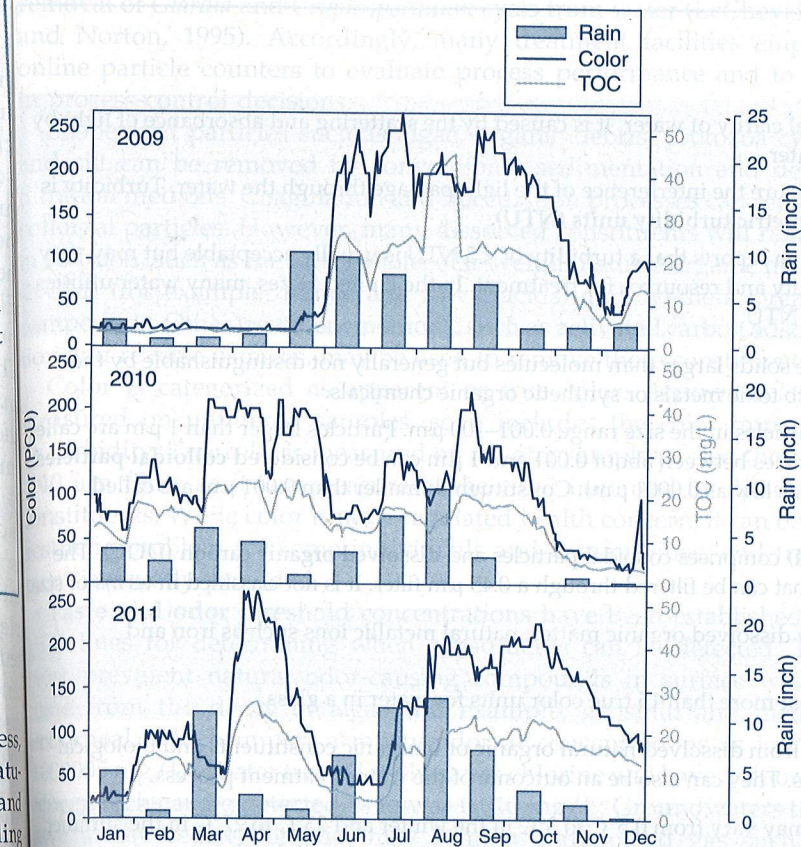


Figure / 8.1 Seasonal Differences in TOC and Color of Hillsborough River Raw Water That Serves the City of Tampa (FL) Water Treatment Plant (2009–2011) The water quality fluctuates largely over the course of the year, impacting the treatment process in many ways. The river's source water is primarily the Green Swamp located in Central Florida. During the wet season (June–September), TOC and color concentrations spike from the large amount of organic matter flushed out of the swamp and river tributaries by heavy rains.

(Courtesy of Dustin Bales, 2012; with permission).

important water quality constituents (specifically TOC and color) change over the season because of seasonal changes in precipitation.

Natural geologic weathering processes can impart dissolved inorganic ions into water, and these can cause problems related to color, hardness, taste, odor, and health. Dissolved organic matter in water, which is derived from decaying vegetation, can impart a yellowish or brownish color to the water. The surrounding terrestrial environment can cause small or colloidal clay particles to be suspended in the water, which impart a turbid or cloudy appearance of the water. Naturally occurring microorganisms such as bacteria, viruses, and protozoa can make their way into natural waters and cause health issues. Synthetic organic chemicals (SOCs) can be released into the environment and cause chronic or acute health problems to humans and aquatic life. Consequently, a water's physical, chemical, and microbiological characteristics need to be considered in the design and operation of a supply and treatment system.

8.2.1 PHYSICAL CHARACTERISTICS

Several aggregate physical characteristics of natural water (also referred to as raw or untreated water) are used to quantify the appearance or aesthetics of the water. These parameters, described in Table 8.3, are turbidity, number and type of particles, color, taste and odor, and temperature.

Test Your Knowledge of Water-Using Behaviors and Water-Saving Opportunities

http://epa.gov/watersense/test_your_watersense.html

Drinking Water at the World Health Organization

http://www.who.int/topics/drinking_water/en/

Table 8.3

Physical Characteristics of Natural Water

Turbidity	Turbidity measures the optical clarity of water. It is caused by the scattering and absorbance of light by suspended particles in the water. A turbidimeter is used to measure the interference of the light passage through the water. Turbidity is reported in terms of nephelometric turbidity units (NTU) . The World Health Organization reports that a turbidity of <5 NTU is usually acceptable but may vary depending upon the availability and resources for treatment. In the United States, many water utilities aim to treat the water to <0.1 NTU.
Particles	Particles in natural waters are solids larger than molecules but generally not distinguishable by the unaided eye. They may adsorb toxic metals or synthetic organic chemicals. Water treatment considers particles in the size range 0.001–100 μm . Particles larger than 1 μm are called suspended solids , while particles between about 0.001 and 1 μm can be considered colloidal particles (though some researchers go as low as 0.0001 μm). Constituents smaller than 0.001 μm are called dissolved particles . Natural organic matter (NOM) comprises colloidal particles and dissolved organic carbon (DOC) . The DOC is the portion of NOM that can be filtered through a 0.45 μm filter. It is not classified in terms of size.
Color	Color is imparted to water by dissolved organic matter, natural metallic ions such as iron and manganese, and turbidity. Most people can detect color at more than 15 true color units for water in a glass.
Taste and odor	Taste and odor can originate from dissolved natural organic or inorganic constituents and biological sources present in raw waters. They can also be an outcome of the water treatment process.
Temperature	Surface water temperatures may vary from 0.5°C to 3°C in the winter and 23°C to 27°C in the summer. Groundwater can vary from 2.0°C to 25°C depending upon location and well depth.

Turbidity measurements of natural waters vary depending upon the water source. Low turbidity measurements (less than 1 NTU) are typical for most groundwater sources, while surface water turbidity varies depending upon the source. In lakes and reservoirs, turbidity is usually stable and ranges from 1 to 20 NTU, but some waters can vary seasonally due to turnover, storms, and algal activity. Turbidity in rivers is highly dependent on precipitation events and can range from less than 10 NTU to more than 4,000 NTU. Because climate change is expected to change weather events in some parts of the world (including the United States), the resulting runoff and erosion may result in decreased or increased seasonal turbidity of some raw-water supplies. We also discussed in the previous chapter how land use impacts the quality of surface runoff.

Turbidity measurements are primarily used for process control, regulatory compliance, and comparison of different water sources. They are also used as an indicator of increased concentrations of microbial water constituents, such as bacteria, *Cryptosporidium* oocysts, and *Giardia* cysts.

Particles found in natural waters can be measured in terms of their numbers and size. Particle counters can measure the number of suspended particles in size ranges generally from 1.0 to 60 μm . Particle removal is important because it has been suggested as an indicator of

removal of *Giardia* and *Cryptosporidium* cysts from water (LeChevallier and Norton, 1995). Accordingly, many treatment facilities employ online particle counters to evaluate process performance and to aid in process-control decisions.

Suspended particles such as algae, organic debris, protozoa cysts, and silt can be removed by conventional sedimentation and depth filtration methods. Coagulation and flocculation processes can remove colloidal particles. However, many dissolved constituents will remain in solution, such as the lower-molecular-weight natural organic matter (NOM) (for example, humic and fulvic acids) and synthetic organic compounds. Other treatment methods, such as activated carbon adsorption and reverse osmosis, may be used to remove these constituents.

Color is categorized as apparent or true color. *Apparent color* is measured on unfiltered samples, so it includes the color imparted by turbidity. *True color* is measured on a water sample passed through a 40 μm filter, so it is a measure of the color imparted by dissolved constituents. While color is not a regulated health concern, it can be an aesthetic problem for some individuals and communities, and treatment is usually provided.

Taste and odor threshold concentrations have been established as guidelines for determining when constituents can be detected. The most prevalent natural odor-causing compounds in surface waters come from the decay of algae (for example, geosmin and methyl isoborneol, which impart a musty odor at concentrations as low as 0.000005 mg/L). Water treated with excess chlorine will have a chlorine odor, which can be detected as low as 0.010 mg/L. Groundwaters that have a low redox potential may contain a dissolved gas such as hydrogen sulfide, which smells like rotten eggs. Waters containing dissolved inorganic compounds such as iron, manganese, and copper may have a metallic taste. The taste of reduced iron (Fe^{2+}) can be detected at 0.04–0.01 mg/L and the taste of reduced manganese (Mn^{2+}) can be detected at 0.4–30 mg/L. Some natural or synthetic organic compounds will impart an objectionable taste to water. Examples of these include phenol, which can be detected at a concentration of 1 mg/L.

Water temperature is very important because it affects many physical and chemical parameters of water, such as density, viscosity, vapor pressure, surface tension, solubility, and reaction rates, which are used in the design and operation of a treatment plant and associated conveyance system.

8.2.2 MAJOR AND MINOR INORGANIC CONSTITUENTS

Table 8.4 summarizes the major dissolved inorganic constituents found in water. Calcium is one of the most abundant cations found in water and is the major constituent of water **hardness** (along with magnesium). Calcium concentrations greater than about 60 mg/L are considered a nuisance by some. Chloride (Cl^-) concentrations in terrestrial waters vary from 1 to 250 mg/L depending on the location, and typical surface water is usually less than 10 mg/L Cl^- . However, waters affected by saltwater intrusion and groundwater that contains trapped brine may have chloride concentrations similar to the ocean. Fluoride exists in natural waters primarily as the anion F^- but can also be

Table / 8.4

Major Dissolved Constituents Found in Water

Constituent	Source	Problem in Water Supply	Range in Natural Waters
Calcium and magnesium	Surface water and groundwater	Above 60 mg/L can be considered nuisance as hardness.	For calcium, less than 1 mg/L to more than 500 mg/L. Surface water concentrations of magnesium are less than 10 mg/L up to 20 mg/L. Groundwater concentrations are less than 30 mg/L up to 40 mg/L.
Chloride	Surface water and groundwater; saltwater intrusion	Above 250 mg/L can impart salty taste. Below 50 mg/L can be corrosive to some metals.	Typical surface water is usually less than 10 mg/L.
Fluoride	Surface water and groundwater Some water utilities add fluoride in the form of sodium fluoride or hydrofluorosilic acid at doses of about 1.0 mg/L	Toxic to humans at concentrations of 250–450 mg/L; fatal at concentrations above 4.0 g/L.	For surface water with total dissolved solids (TDS) concentrations less than 1,000 mg/L, fluoride is usually less than 1.0 mg/L.
Iron and manganese	Surface water and groundwater	Taste threshold of iron for many consumers is around 0.01 mg/L. Iron can impart a brownish color to laundry and bathroom fixtures. Manganese ion can impart a dark brown color. At concentrations around 0.4 mg/L, manganese can impart an unpleasant taste to water and can stain laundry and fixtures.	In oxygenated surface waters, the concentration of total iron is usually less than 0.5 mg/L. In groundwater that has low bicarbonate and dissolved oxygen, iron concentrations can range from 1.0 to 10.0 mg/L. The concentration of manganese ion in surface water and groundwater may be less than 1.0 mg/L.
Nitrate	Surface water and groundwater can contain high concentrations of nitrate from runoff from fertilizers found in urban and agricultural watersheds.	Very high nitrate concentrations may produce infant methemoglobinemia.	
Sulfur	Surface water and groundwater	Groundwater low in dissolved oxygen can contain reduced sulfur compounds, which impart objectionable odors such as that of rotten eggs. Sulfates are also corrosive in concrete structures and pipes.	Sulfate concentrations in freshwater can approach 10 mg/L.

associated with ferric ion, aluminum, and beryllium. Some water utilities add fluoride in the form of sodium fluoride or hydrofluorosilic acid at concentrations of about 1.0 mg/L.
Iron is abundant in geological formations and is frequently found in water. If not removed, it can impart a brownish color to laundry and

bathroom fixtures. At concentrations around 0.2–0.4 mg/L, manganese can impart an unpleasant taste to the water and stain laundry and fixtures.

Surface water can contain high concentrations of nitrate (and other forms of nitrogen) from urban and agricultural runoff. Groundwater can also contain high concentrations of nitrate, especially in agricultural areas, where ammonia fertilizers are biochemically converted to nitrate in the soil or areas impacted by on-site treatment such as faulty septic tanks. Nitrate is regulated because high concentrations may produce infant methemoglobinemia.

Sulfur can occur as sulfates (CaSO_4 , Na_2SO_4 , MgSO_4) and reduced sulfides (H_2S , HS^-). Sulfides can be found in water where there is significant organic decomposition that results in anoxic conditions. Groundwater low in dissolved oxygen can contain reduced sulfur that imparts objectionable odors. Sulfates are also corrosive in concrete structures and pipes.

Several minor inorganic constituents are sometimes a significant health concern or diminish water quality. Examples include copper, chromium, nickel, mercury, strontium, and zinc. Some of these constituents are the result of the surrounding natural environment, while others are present due to human activities. For example, some industrial sites that use arsenic as a wood preservative have contaminated water supplies, while naturally occurring arsenic is widespread throughout much of the world. In this latter case, arsenic is found mostly as a solid in the mineral form. However, it can be found dissolved in groundwater in the form of arsenite (H_3AsO_3) and arsenate (H_2AsO_4^- , HAsO_4^{2-}) species. In contrast, lead contamination is usually associated with human activities that even include leaching from old distribution systems.

Lead in Drinking Water

<http://www.epa.gov/safewater/lead>

Global Arsenic Crisis

<http://www.who.int/topics/arsenic/en/>

Application / 8.2 The Global Arsenic Crisis

As Table 8.5 shows, naturally occurring arsenic is widespread in water supplies throughout the world. Unfortunately, when humans are exposed over long

periods to low concentrations of arsenic from consuming contaminated water, several forms of cancer can develop. The World Health Organization has

Table / 8.5

Global Locations Where Naturally Occurring Arsenic Has Been Detected in Drinking-Water Supplies

Region	Specific Countries
Asia	Bangladesh, Cambodia, China, India, Iran, Japan, Myanmar, Nepal, Pakistan, Thailand, Vietnam
Americas	Argentina, Chile, Dominica, El Salvador, Honduras, Mexico, Nicaragua, Peru, United States
Europe	Austria, Croatia, Finland, France, Germany, Greece, Hungary, Italy, Romania, Russia, Serbia, United Kingdom
Africa	Ghana, South Africa, Zimbabwe
Pacific	Australia, New Zealand

SOURCE: Petrusevski et al., 2007.

Application / 8.2 (continued)

accordingly set a drinking-water guideline for arsenic of 10 $\mu\text{g}/\text{L}$ (10 ppb).

The magnitude of the problem is most serious in Bangladesh and West Bengal (India). In the 1970s and 1980s, 4 million hand-pump wells were installed in Bangladesh and India to provide people there with a pathogen-free drinking-water supply. The presence of arsenicosis began to appear in the 1980s, shortly after the well installation program. By the early 1990s, it was determined that the arsenic poisoning was originating from these wells. The arsenic is naturally occurring.

Today it is estimated that, every day in Bangladesh, up to 57 million people are exposed to arsenic concentrations greater than 10 $\mu\text{g}/\text{L}$. In West Bengal, an estimated 6 million people are exposed to arsenic concentrations between 50 and 3,200 $\mu\text{g}/\text{L}$. The magnitude of the problem shows why some have called this the greatest mass poisoning of humans that has ever occurred.

The most commonly used arsenic removal systems in both the developed and developing world are based on coagulation-separation and adsorption processes. Membrane filtration (such as reverse osmosis and nanofiltration) is also effective at removing arsenic from water; however, it is not practical in much of the world because of the high costs involved. Accordingly, appropriate technologies have been developed to treat this water. Figure 8.2 shows one such technology.

This unit is installed directly at the hand-pumped wells that were installed in the 1970s and 1980s. It

requires no electricity or chemical addition. The unit is packed with granular activated alumina, which removes the arsenic from the water. The unit can be regenerated with caustic soda about every 4 months. The community is instructed to dispose of the arsenic-laden sludge in a pit lined with bricks. After 10 years of typical operation, it is estimated that the volume of sludge generated will occupy 56 ft^3 .

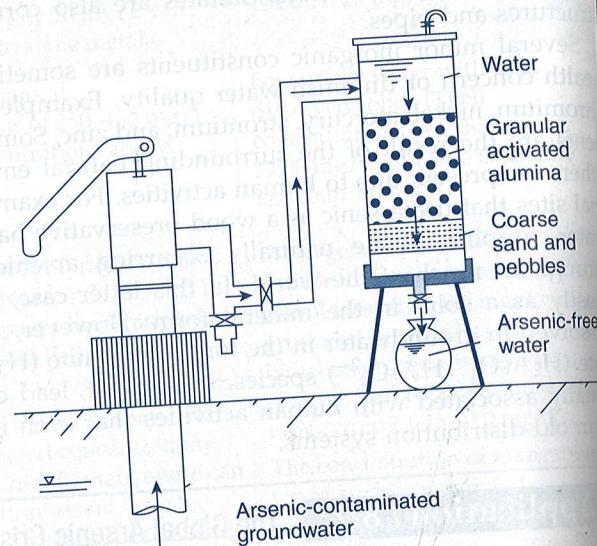


Figure / 8.2 Well Head Arsenic Removal Unit Developed by Dr. Arup Sangupta and Others at Lehigh University.

8.2.3 MAJOR ORGANIC CONSTITUENTS

Organic constituents found in water can either be naturally occurring or associated with human activities. Natural organic matter (NOM) in water is the result of the complexation of soluble organic material derived from biochemical degradation of vegetation in the surrounding environment. NOM occurs in all waters and is measured as total organic carbon (TOC). Typical TOC concentrations in natural waters range from less than 0.1 to 2.0 mg/L in groundwater, 1.0–20 mg/L in surface waters, and 0.5–5.0 mg/L in seawater. Table 8.6 summarizes the impact NOM can have on drinking-water treatment processes.

Table / 8.6

Effect of Natural Organic Matter (NOM) on Water Treatment Processes

Water Treatment Process	Effect
Disinfection	NOM reacts with, and consumes, disinfectants, which increase required dose to achieve effective disinfection.
Coagulation	NOM reacts with, and consumes, coagulants, which increase required dose to achieve effective turbidity removal.
Adsorption	NOM adsorbs to activated carbon, which depletes adsorption capacity of the carbon.
Membranes	NOM adsorbs to membranes, clogging membrane pores, and fouling surfaces. This leads to decline in water passed through the membrane.
Distribution system	NOM may lead to corrosion and slime growth in distribution systems (especially when oxidants are used during treatment).

SOURCE: Adapted from Crittenden et al., 2012.

Anthropogenic organic constituents found in water are associated with industrial activity, land use by agriculture, urban runoff, and municipal effluents from wastewater treatment plants. Most of these organic contaminants are classified as **synthetic organic chemicals (SOCs)**. Representative SOC are found in fuels, cleaning solvents, chemical feedstocks, and herbicides and pesticides. **Emerging chemicals of concern** are now found in water and wastewater from the use of personal-care and pharmaceutical products.

8.2.4 MICROBIAL CONSTITUENTS

Potable water must be free from pathogenic microorganisms. As just one example of the global magnitude of the problem, the WHO reports that diarrhea contributed 4.7 percent of the global burden of disease in 2011. Of that 4.7 percent, approximately 88 percent was caused by unsafe water, sanitation, and hygiene.

Pathogens are microorganisms that cause sickness and disease. Pathogens include many classes of microorganisms, among them viruses, bacteria, protozoa, and helminths.

Details about some representative pathogenic organisms found in untreated water and associated health effects are provided in Table 8.7. Note the small size of pathogens that can prevent their removal via conventional gravity sedimentation processes. Because there are many different water-based pathogens, monitoring and detecting all of them would require a prohibitive amount of resources. Consequently, **indicator organisms** (such as **coliforms**) have been identified and are used to monitor the microbial water quality.

At present, the EPA requires water utilities to monitor their water distribution system monthly for **total coliforms**. The total coliform rule maximum contaminant level is based on frequency of detection (no

Pharmaceuticals and Personal-Care Products

<http://epa.gov/ppcp/faq.html>

How's Your Local Drinking Water?

<http://water.epa.gov/drink/local/index.cfm>

Table 8.7

Representative Pathogenic Organisms in Raw-Water Supplies

Pathogen(s)	Type	Health Effects in Healthy Persons	Normal Habitat
<i>Vibrio cholera</i> Shape: wormlike Size: 0.5 by 1–2 μm	Bacteria	Classic cholerae—explosive diarrhea and vomiting without fever followed by dehydration; abnormally low blood pressure and temperature; muscle cramps; shock; coma followed by death	Human stomach and intestines
<i>Salmonella</i> (several species) Shape: rod Size: 0.6 μm	Bacteria	<i>S. typhi</i> species causes enteric fever, headaches, malaise, and abdominal pain	Intestines of warm-blooded animals
<i>Shigella dysenteriae</i> Shape: round Size: 0.4 μm	Bacteria	Bacillary dysentery: abdominal pain, cramps, diarrhea, fever, vomiting, blood, and mucus in stools	Human stomach and intestines
<i>Escherichia coli</i> Shape: rod Size: 0.3–0.5 by 1–2 μm	Bacteria	Diarrhea	Intestines of warm-blooded animals
Poliovirus types 1, 2, 3 Shape: round Size: 28–30 nm	Virus	Fever, severe headache, stiff neck and back, deep muscle pain, and skin sensitivity	Human intestinal tract
Human adenovirus type 2 Shape: 12 vertices Size: 70–90 nm	Virus	Severe infections in lungs, eyes, urinary tract, genitals; some strains affect intestines	Human intestinal tract
Rotavirus A Shape: round Size: 80 nm	Virus	Severe diarrhea and dehydration	Human intestinal tract
<i>Cryptosporidium parvum</i> Type 1 oocyst Shape: ellipsoidal Size: 3–5 μm Sporozoite and merozoites Shape: wormlike Size: 10 by 1.5 μm	Protozoa	Severe diarrhea, abdominal pain, nausea or vomiting, and fever	Human intestinal tract
<i>Giardia lamblia</i> Shape: single-celled flagellated protozoa Size: 9–15 μm long, 5–15 μm wide, 2–4 μm thick	Protozoa	Sudden diarrhea, abdominal cramps, bloating, cramps, and weight loss	Human intestinal tract
<i>Schistosoma haematobium</i> A wormlike organism	Helminthic	Squamous cell carcinoma of the bladder; urolithiasis; ascending urinary tract infection; urethral and ureteral stricture with subsequent hydronephrosis; renal failure	Blood vessels of the human bladder and mammals

more than 5 percent for systems collecting at least 40 samples per month) or the combination of a positive *Escherichia coli* sample (or fecal coliforms) with a positive total coliform sample. While the total coliform test can provide a good indication of fecal contamination, it cannot prove that the source water is safe. Other methods must be used to confirm the absence of longer-surviving organisms such as viruses and spores.

8.3 Water Quality Standards

The Safe Drinking Water Act (SDWA) (Public Law 93–523) was passed by the U.S. Congress in 1974 and amended in 1986 and 1996 to protect public health by regulating the public water supply. Under this law, the primary responsibility of setting the water quality regulations was moved from the states to the EPA. To protect public health, EPA established primary drinking-water standards by setting health-based **maximum contaminant level goals (MCLGs)** and **maximum contaminant levels (MCLs)** for a large number of pollutants.

The MCL is the enforceable standard and is based not only on health and risk assessment information, but also on costs and the availability of technology. The MCLGs are based solely on health and risk assessment information.

Table 8.8 provides the MCLGs and MCLs for several important chemicals found in water supplies and their potential health effects. A similar set of MCLs has been established by the World Health Organization (see www.who.org).

Table 8.8

Representative Chemicals Found in Water and Their Maximum Contaminant Level Goals (MCLGs) and Maximum Contaminant Levels (MCLs) MCLGs are based solely on health and risk assessment information. MCLs are based not only on health and risk assessment information, but also on costs and the availability of technology.

Chemical	Maximum Contaminant Level Goal (mg/L)	Maximum Contaminant Level (mg/L)
Synthetic Organic Chemicals (SOCs)		
2,4-D (2,4-dichlorophenoxyacetic acid)	0.07	0.07
Alachlor	0	0.002
Atrazine	0.003	0.003
Benzo(a)pyrene	0	0.0002
Chlordane	0	0.002
Lindane	0.0002	0.0002
Polychlorinated biphenyl (PCB)	0	0.0005
Volatile Organic Chemicals (VOCs)		
1,1-Dichloroethylene	0.007	0.007
1,1,1-Trichloroethane	0.2	0.2

(continued)

Safe Drinking Water Act

<http://www.epa.gov/safewater/edwa/index.html>

Interactive Presentation to Understand the Safe Drinking Water Act

<http://water.epa.gov/learn/training/dwatrain/training.cfm>

Safe Drinking Water Hotline 1-800-426-4791

Information about drinking-water and groundwater programs authorized under the SDWA.



Class Discussion

At present, EPA has developed MCLs for over 90 contaminants, even though there are tens of thousands of commonly used chemicals in commerce. It has thus been a daunting task for government regulators to keep pace with the introduction of new chemicals into commerce and prevent or minimize public exposure to them. How would more widespread implementation of green chemistry and green engineering (discussed in Chapters 3 and 6) that are intended to reduce chemical hazard affect issues of regulation and treatment?

Table / 8.8

(continued)

1,2-Dichloroethane	0	0.005
Benzene	0	0.005
Carbon tetrachloride	0	0.005
cis-1,2-Dichloroethylene	0.07	0.07
Dichloromethane	0	0.005
Ethyl benzene	0.7	0.7
Toluene	1	1
Tetrachloroethylene	0	0.005
Trichloroethylene	0	0.002
Vinyl chloride	0	10
Xylenes (total)	10	10
Inorganics		
Arsenic	0	0.01
Cadmium	0.005	0.005
Chromium (total)	0.1	0.1
Cyanide	0.2	0.2
Fluoride	4	4
Lead (at tap)	0	0.015 (action level)*
Mercury	0.002	0.002
Nitrate (as N)	10	10
Nitrite (as N)	1	1

*The concentration of a contaminant which, if exceeded, triggers treatment or other requirements which a water system must follow.
SOURCE: EPA 2012 Edition of the Drinking Water Standards and Health Advisories.

Application / 8.3

Developing a Drinking-Water Standard from Toxicity Data

In this example we demonstrate one way EPA develops a drinking-water standard from toxicity information. In this case we will use EPA's decision to regulate the noncarcinogen perchlorate (ClO₄⁻). EPA reports that perchlorate (ClO₄⁻) is both a naturally occurring and manmade chemical. It is used to produce rocket fuel, fireworks, flares, and explosives. It can also be found in bleach and some fertilizers. Monitoring data shows that >4 percent of public water systems have detected perchlorate, and 5–17 million people may be exposed to drinking water containing perchlorate.

Perchlorate is an important issue when protecting human health, because scientific research indicates it can disrupt the thyroid's ability to produce important developmental hormones that are critical for normal brain development and growth of fetuses, infants, and young children. To give you an idea of the effort involved in developing a

drinking-water standard for one chemical, in this process EPA considered input from their Science Advisory Board and almost 39,000 public commenters since 2007.

EPA decided to regulate perchlorate under the SDWA (see <http://water.epa.gov/drink/contaminants/unregulated/perchlorate.cfm>). In the process of developing a drinking-water standard, EPA first develops a primary drinking-water standard for perchlorate by setting a health-based MCLG. After this is accomplished, they set the enforceable MCL.

In this case, the drinking-water standard is related to toxicity information provided by the reference dose (RfD). In Chapter 6, we defined the RfD as an estimate, with uncertainty spanning perhaps an order of magnitude, of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. The RfD for

Application / 8.3 (continued)

perchlorate can be obtained from the data available in the Integrated Risk Information System (IRIS) (<http://www.epa.gov/IRIS/>). IRIS reports the RfD for perchlorate is 0.7 µg per kg of body weight per day (0.7 µg/kg/day). This RfD is based on the No Observed Effect Level (NOEL) of 7 µg/kg/day and application of an uncertainty factor (UF) of 10 to account for differences in sensitivity between the healthy adults and the most sensitive population, that is, fetuses of pregnant women who might have hypothyroidism or iodide 21 deficient.

So how does EPA go from the RfD to a drinking-water standard? The health-based MCLGs EPA will set for drinking water can be determined as:

$$MCLG (\mu\text{g/L}) = \frac{RfD \left(\frac{\mu\text{g}}{\text{kg} \cdot \text{day}} \right) \times \text{body weight (kg)}}{\text{drinking water intake} \left(\frac{\text{L}}{\text{day}} \right)} \times RSC$$

In this equation, EPA assumes the default values for body weight (70 kg) and drinking-water ingestion rate (2 L/day). The RSC is the relative source contribution and is the percentage of the RfD that remains for drinking water after other sources of perchlorate exposure occurs. Remember that you could intake

perchlorate through other routes of exposure besides drinking water. The RSC is based on studies performed by the Food and Drug Administration (FDA) and in this case, EPA is proposing to use an RSC of 62% (so the RSC = 0.62) for a pregnant woman. This means that 62% of a pregnant woman's exposure to perchlorate would be through drinking water.

If you place these values into the above equation, you will obtain an MCLG for perchlorate of 15 µg/L (15 ppb) in drinking water.

Remember from our reading in this chapter that the MCLG is a nonenforceable goal defined under the SDWA as "the level at which no known or anticipated adverse effects on the health of persons occur and which allows an adequate margin of safety." The SDWA specifies that the enforceable MCL be set as close to the MCLG as feasible using the best available technology, treatment techniques, and other means (considering cost). This process was not yet finalized as we were writing this book, but it does show the MCL that EPA will eventually set for perchlorate will be ≥15 µg/L.

Information and text courtesy of U.S. Environmental Protection Agency.

8.4 Overview of Water Treatment Processes

The typical unit processes used for the treatment of surface water and brackish waters are shown in Figure 8.3. Table 8.9 summarizes the unit processes associated with significant removal of particular water constituents. Treatment of surface waters (Figure 8.3a) mostly requires the removal of particulate matter and pathogens. Removing particles also

Table / 8.9

Unit Processes That Remove a Significant Amount of Raw-Water Constituents

Constituent	Unit Process(es)
Turbidity and particles	Coagulation/flocculation, sedimentation, granular filtration
Major dissolved inorganics	Softening, aeration, membranes
Minor dissolved inorganics	Membranes
Pathogens	Sedimentation, filtration, disinfection
Major dissolved organics	Membranes, adsorption