A SunCam online continuing education course

Protecting Drinking Water from Pathogens

by

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Course Outline:

Overview and History
Biological Contaminants
Microbial Indicators
Water Sources and Risks
Water Treatment and Disinfection
Log Removal
Distribution System Approaches
Water Storage Tank Approaches
Helpful References
Examination

Overview and History

Drinking water is, and always has been, susceptible to transmitting waterborne diseases from pathogens. Modern methods of treating and disinfecting water have greatly decreased the risk of getting sick from drinking water, but outbreaks still occur and the threat remains. This course aims to empower engineers to help in the ongoing fight to eliminate pathogens from drinking water.

Let's start with a little history of waterborne diseases in public water systems. Regular access to clean water has always been a struggle for humans and nearly every other mammal for that matter. In general, where there is clean water there is life.

Early settlements dating back to 8,000 BCE utilized springs and wells as a water source. The quality of the water was examined by the senses: taste, smell, appearance, and temperature. As civilization developed and communities grew in size, access to clean water become a primary health concern for society.

The Greeks and Romans developed methods to improve water quality through the use of settling tanks, sieves, filters, and the boiling of water. Medical records from the antiquity era state that the boiling of water diminishes the risk of acquiring an illness. The practice of boiling water for disinfection is still practiced today.

Another lesson learned from the antiquity era is the separation of human waste from drinking water. Waterborne infections are thought to have been the leading cause of death for those living in the city. And the vast majority of waterborne diseases came from poor handling of human feces which ultimately contaminated the drinking water. To protect against this cross-contamination, many Roman cities had sewer networks underground which were kept separate from the aqueducts and cisterns which held fresh water for bathing and drinking. See Figures 1 and 2.

Figure 1: Roman aqueduct that carried clean water to the city of Caesarea Maritima.

Figure 2: Ruin of a Roman-era building in Pompeii with sewer pipes seen in the walls. The pipes carried wastewater down to larger collection pipes below the street.

In the 19th century, modern water supply and sanitation systems were implemented in towns across Europe. Indoor plumbing systems and bathroom fixtures were invented and quickly grew in popularity. But the greatest development in that century was the scientific discovery of the role of drinking water in the transmission of several important diseases, such as cholera, dysentery, and typhoid fever. The microbes causing these diseases were finally discovered and identified, thereby giving engineers new insights into how to eliminate them from public water systems.

The following advances soon followed the identification of the microbes:

- Water quality was monitored by chemical and microbiological examination, in addition to the traditional sensory methods.
- The filtering of an entire public water supply first began in the late 19th century. The design of large-scale water treatment systems soon followed.
- Systematic chlorination of drinking water started in the early 20th century. Soon after, disinfection by chlorination became the primary means of eliminating waterborne diseases all around the world. See Figure 3.

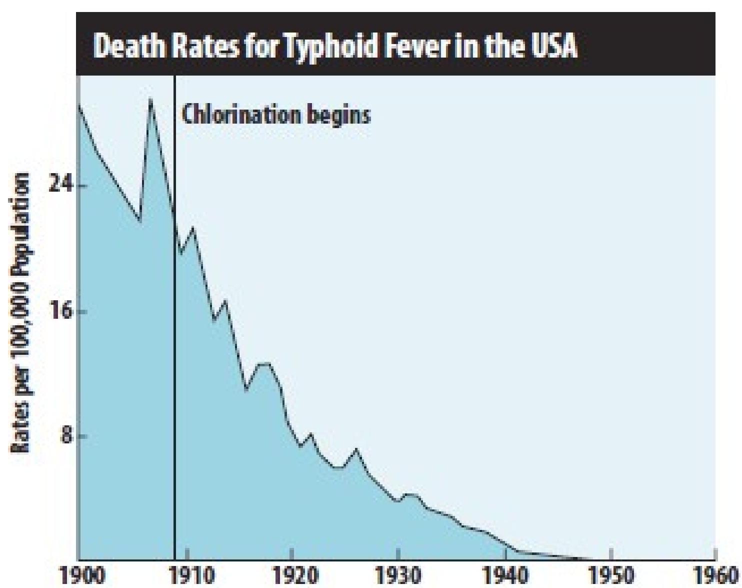


Figure 3: Chart showing the drop in typhoid fever infections after chlorination of drinking water began in 1909. Typhoid fever is caused by the bacteria *Salmonella enterica serotype Typhi.*

In the 20th century, technology advanced to allow for efficiently treating and disinfecting large flows of drinking water. Public water systems became cleaner and cleaner with each passing decade. Infection rates decreased for all known waterborne diseases.

This brings us to the 21st century, in which public health problems caused by biologically polluted water are no longer urgent concerns in society. However, waterborne disease outbreaks are still commonplace around the world, resulting in extreme illness and death. According to the World Health Organization, waterborne diseases account for approximately 4 percent of the global burden of disease, with around 1.5 million deaths a year. Engineers are entrusted to continue the age-old mission of protecting people from potential outbreaks of waterborne diseases by improving the designs of public water systems.

Biological Contaminants

The Safe Drinking Water Act defines "contaminant" as any physical, chemical, biological, or radiological substance or matter in water. In other words, anything other than H_2O water molecules. Drinking water may reasonably be expected to contain at least small amounts of some contaminants while still being safe to drink.

The US Environmental Protection Agency (EPA) officially groups contaminants into these four categories:

1. **Physical** contaminants primarily impact the physical appearance or other physical properties of water. Examples of physical contaminants are sediment or organic material suspended in the water from soil erosion.
2. **Chemical** contaminants are elements or compounds. These contaminants may be naturally occurring or man-made. Examples of chemical contaminants include nitrogen, bleach, salts, pesticides, metals, toxins produced by bacteria, and human or animal drugs.
3. **Biological** contaminants are organisms in the water. They are also referred to as microbes or microbiological contaminants. Examples of biological or microbial contaminants include bacteria, viruses, protozoans, and parasites.
4. **Radiological** contaminants are chemical elements with an unbalanced number of protons and neutrons resulting in unstable atoms that can emit ionizing radiation. Examples of radiological contaminants include cesium, plutonium, and uranium.

Consider an example of boiling a hotdog in a jar of pure water (H_2O), as shown in Figure 4. What contaminants could be in the water from each of the four categories?

Figure 4: A hotdog being boiled in a jar of water.

Possible contaminants include:

1. Physical: The hotdog itself
   Pieces of hotdog floating in the water
2. Chemical: Organics from the hotdog
   Cleaning chemical residue from the jar
   Remnants of inactivated microorganisms
3. Biological: Bacteria from inside the hotdog that survives the boiling
4. Radiological: None

If the water is boiled for at least a minute, likely all microorganisms would be effectively killed (also called inactivated), and thus not considered a biological contaminant. However, the remnants of the inactivated microorganisms could be considered a chemical contaminant, especially as the dead organic matter may deplete the water quality. Fortunately, a hot dog typically does not contain many microorganisms, assuming it is refrigerated and not expired.

This course focuses on biological contaminants. Biological contaminants can be grouped according to their taxa or classifications, as shown in Figure 5.

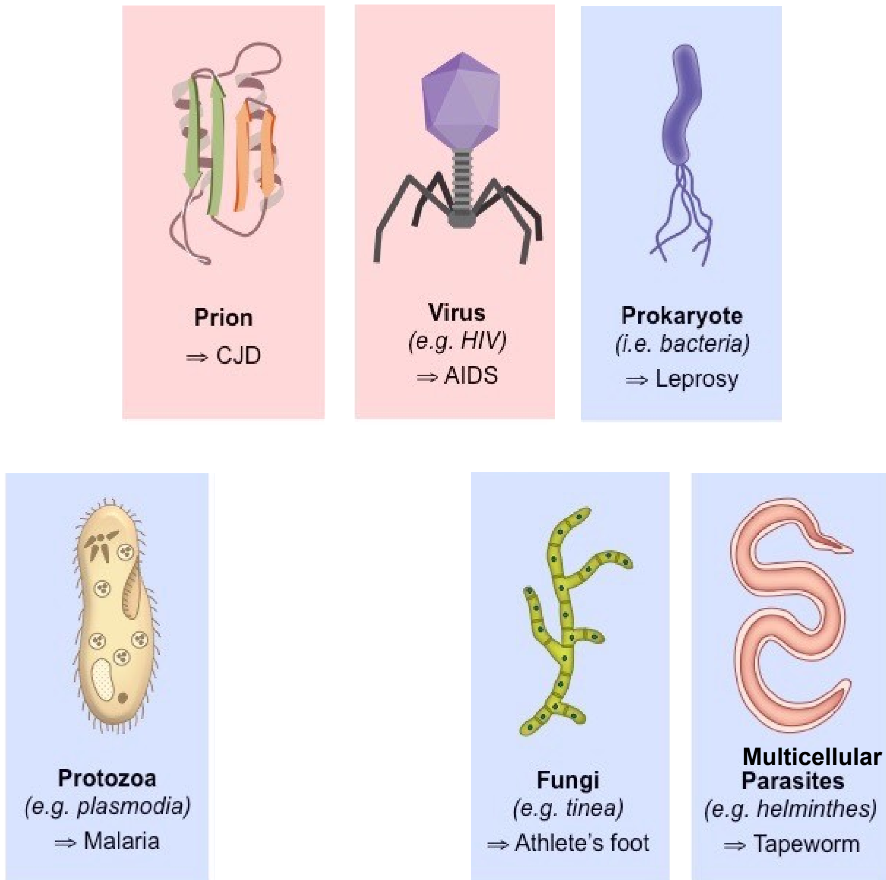


Figure 5: Classifications of microorganisms in order of size, from Prion (smallest) to Multicellular Parasites (largest). Important protozoa include Cryptosporidium and Giardia. Archaea are not shown as there are no known waterborne pathogens.

The majority of microorganisms found in water are harmless when consumed. If they are present in great numbers, they may result in a stomachache or diarrhea, but no serious illness. The harmful microorganisms are classified as pathogenic. Pathogenic microorganisms are responsible for infectious diseases. Diseases that can be spread by drinking water are called waterborne diseases, or waterborne illnesses. The vast majority of waterborne diseases are caused by viruses, bacteria, and protozoa that live in human intestines and feces, and happen to be able to survive in water for a limited amount of time. They cause what are called *excreta-related infections* via the fecal-oral route of transmission. Water becomes the medium for transferring the microorganisms to the mouth.

In the United States, the Center for Disease Control and Prevention (CDC) tracks each waterborne disease and assigns the following classifications based on infection trends:

- Declining
- Stable
- Emerging
- Re-emerging

Although the number of outbreaks has significantly decreased in the last century, there are still emerging waterborne illness outbreaks that occur from time to time in the United States and around the world, as depicted in Figure 6. The greatest decrease has been with *unidentified* outbreaks. This is attributed to medical advances that allow for the identification of the exact pathogen causing the illness. The greatest increase has been with the bacterial Legionella, which is a bacteria that naturally live in water and thus is not an excreta-related pathogen. The Distribution System Design and Water Storage Tank Design Sections of this course include approaches to protect against Legionella.

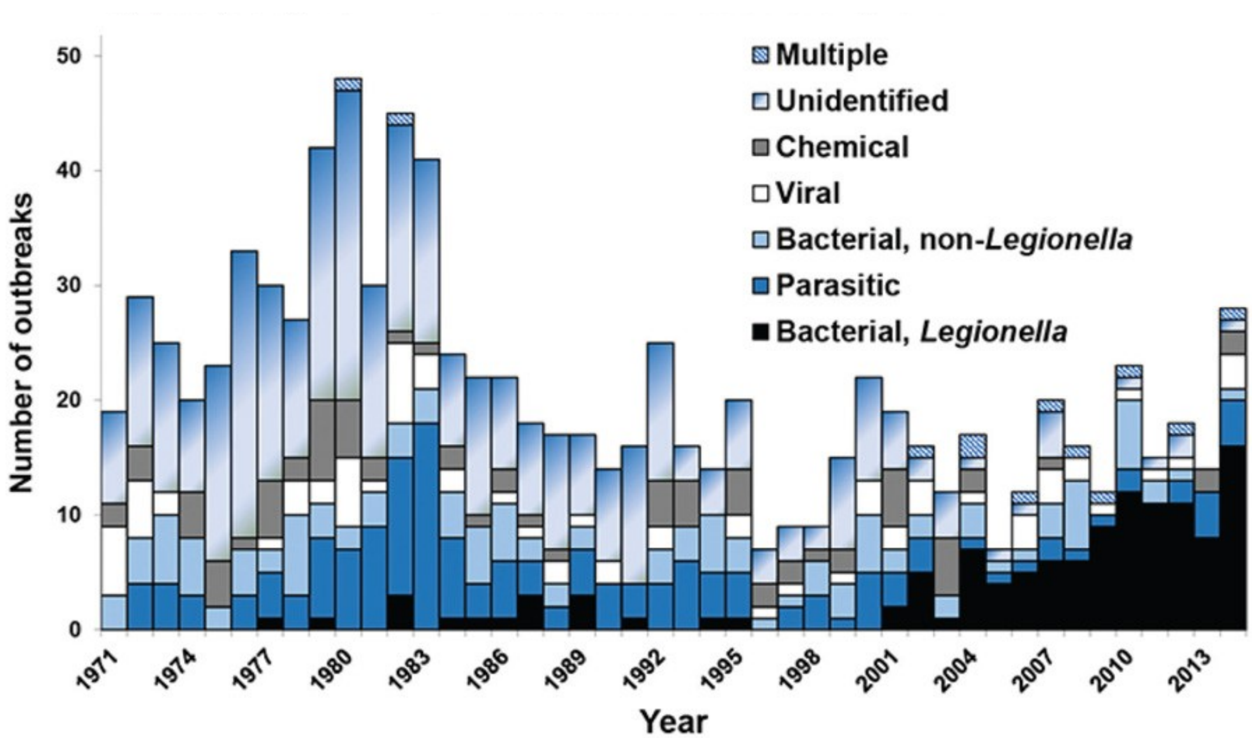


Figure 6: Chart of drinking water-associated outbreaks in the United States by year. The largest decrease has been from "unidentified cases". The largest increase has been from legionella bacteria. Source: Benedict et al., 2017.

Outbreaks can result from one or more of the following causes:

- Poor system design,
- Contaminated water source,
- Problem with treatment or disinfection,
- Inadequate maintenance,
- Poor operation decisions,
- Inadequate redundancy or standby power
- Extreme events that damage the water system

This course will empower engineers to identify these causes and take steps to prevent drinking water-associated outbreaks. An example of a recent outbreak is in Puerto Rico in September 2017, when Hurricane Maria damaged water treatment and disinfection systems and caused a lack of standby power, resulting in a loss of pressure in the water distribution system. An outbreak of leptospirosis illnesses occurred which was linked to contaminated drinking water. Figure 7 shows the spike in cases just after the hurricane. Leptospirosis, or Weil's disease, is caused by the bacteria leptospira, which naturally lives in stagnant water such as ponds and shallow lakes.

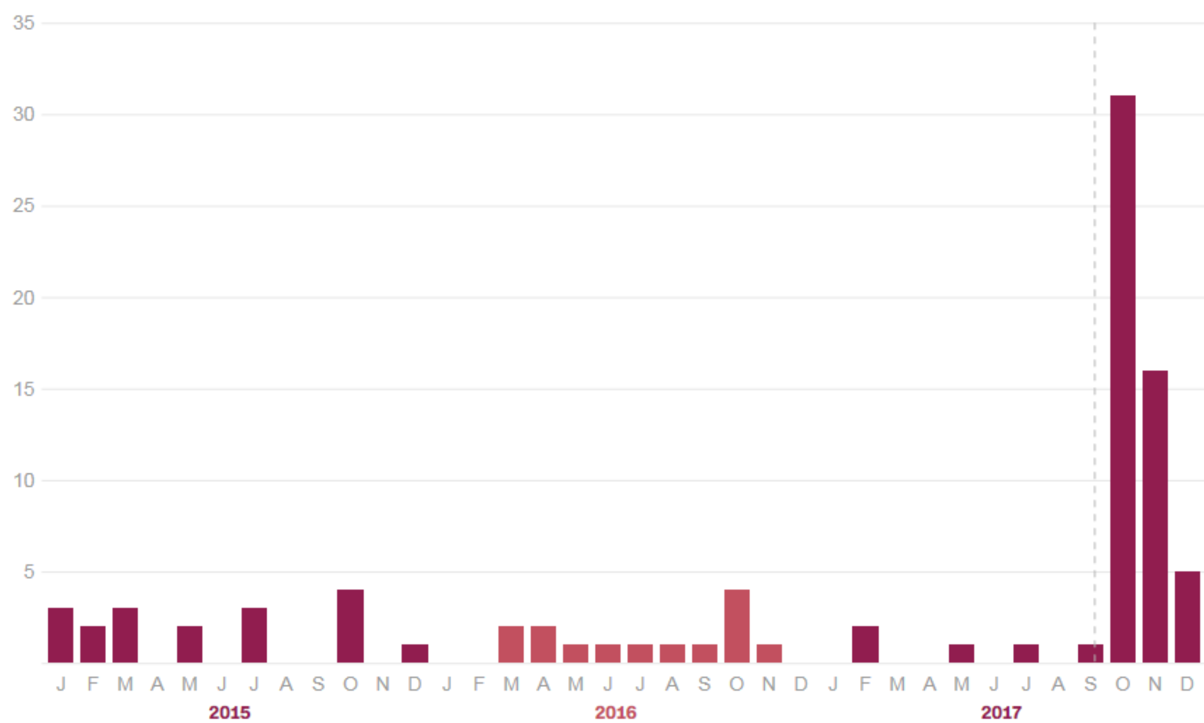


Figure 7: Leptospirosis Illnesses in Puerto Rico
Source: Puerto Rico Department of Health

Microbial Indicators

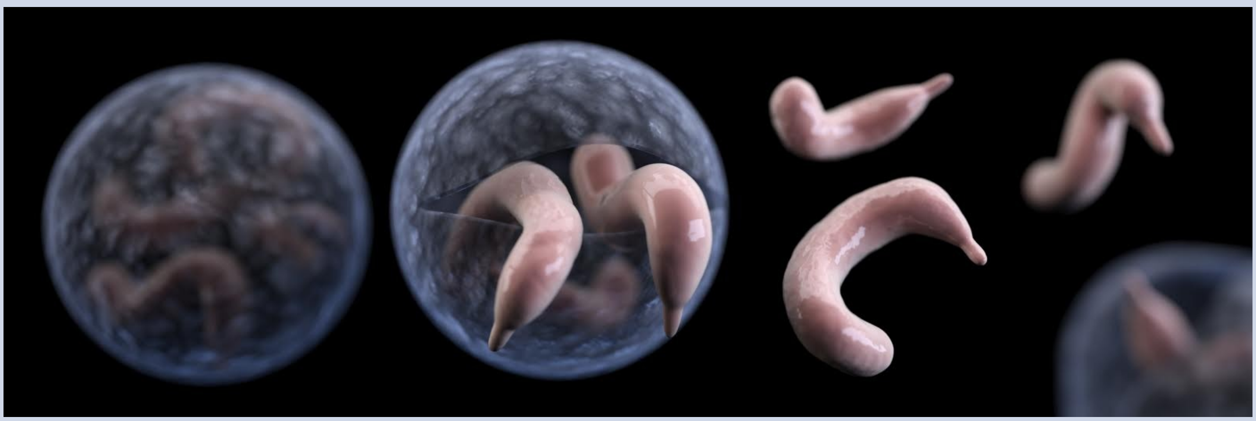
Ideally, water treatment systems would be designed to eliminate every known pathogen and be continuously tested for the presence of those pathogens. This would be a monumental task, as there are hundreds of potential pathogens and new pathogens are still being discovered. Instead, health agencies have developed *microbial indicators* (also called indicator organisms) that can be used for design and testing. Microbial indicators are key organisms or tests that indicate biological contamination and health risk. Some indicators are for particular pathogens that are either common or difficult to eliminate. Other indicates are for the general presence of microorganisms.

The EPA's Surface Water Treatment Rules require drinking water systems to monitor and control the following seven microbial indicators:

1. Cryptosporidium
2. Giardia Lamblia
3. Enterovirus
4. Legionella
5. Turbidity
6. Heterotrophic plate count (HPC)
7. Total Coliforms

Each indicator is summarized in the following tables.

1. Cryptosporidium				
Source	**Microbial Agent**	**Classification**	**Health Effect**	**EPA Limit**
Feces	Cryptosporidium Parvum	Protozoa	Gastrointestinal illness (Cryptosporidiosis)	0

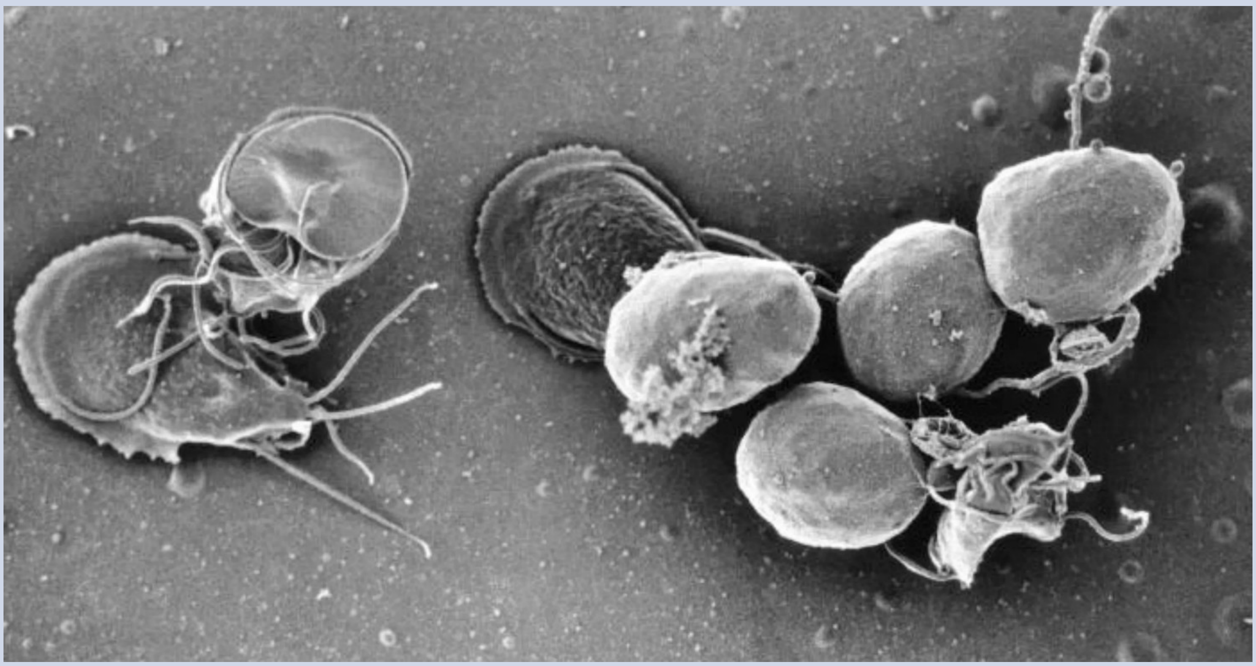


Cryptosporidium sporozoites being excreted from circular oocysts.
Source: Centers for Disease Control and Prevention

Cryptosporidium oocysts are common and widespread in ambient water. The oocysts have a level of resistance to common disinfection practices such as chlorination. In 1993 in Milwaukee, Wisconsin, an outbreak occurred with an estimated 400,000 people becoming ill. At that time, there was poor water quality in the water supply (from Lake Michigan) and there were problems with the coagulation-filtration treatment process which increased the turbidity of the treated water and resulted in inadequate removal of the Cryptosporidium oocysts.

EPA Requirements:
Include a water filtration system that is capable of removing at least 99 percent (2-log) of Cryptosporidium oocysts. Any unfiltered water systems are required to include Cryptosporidium in their watershed control provisions.

2. Giardia Lamblia				
Source	**Microbial Agent**	**Classification**	**Health Effect**	**EPA Limit**
Feces	Giardia Lamblia	Protozoa	Gastrointestinal illness (Giardiasis)	0

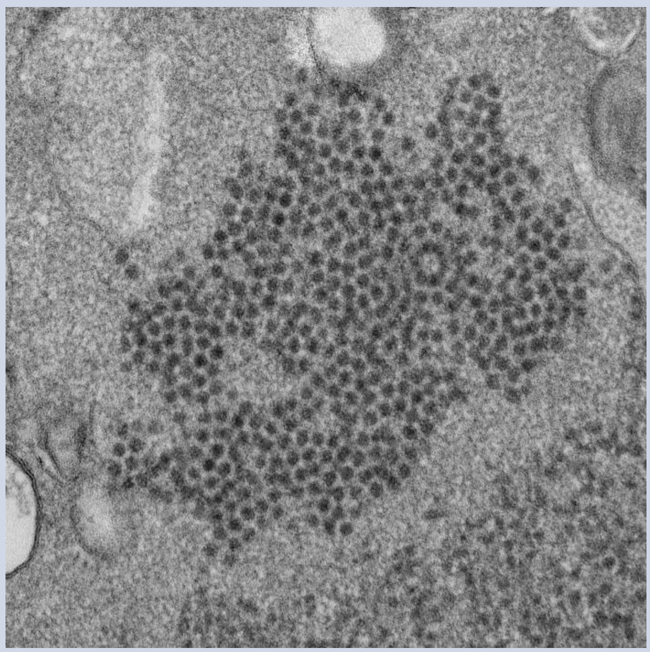


Giardia lamblia culture with two trophozoites (feed stage) on left and four cysts (dormant stage) on right.
Source: Centers for Disease Control and Prevention

Giardia is the most commonly identified pathogen in waterborne outbreaks in the United States. Giardia is common in many mammals. Giardia cysts have tough walls that allow them to survive in water systems for extended periods and provide some level of resistance to disinfectants.

EPA Requirements:
Treatment systems are to remove a minimum of 99.9% (3-log) removal of giardia lamblia.

3. Viruses (enteric)				
Source	**Microbial Agent**	**Classification**	**Health Effect**	**EPA Limit**
Feces	Enterovirus (polio and non-polio)	Virus	Gastrointestinal illness, delirium, headache, fever, seizures, paralysis	0

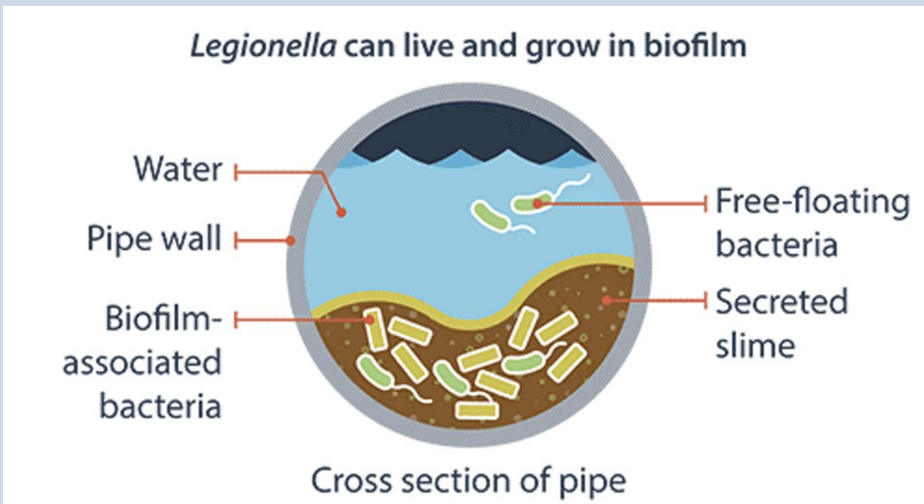


An electron micrograph showing spherical particles of Enterovirus D68.
Source: Cynthia S. Goldsmith and Yiting Zhang, CDC

Enteroviruses are a group of small viruses. There are two subgroups of enteroviruses: viruses that cause polio and viruses that cause non-polio-related diseases. The non-polio enteroviruses are second only to cold viruses as the most common cause of viral infections in humans. Viruses may enter the water source through polluted stormwater, sewage overflows, or cross-connections.

EPA Requirements:
Treatment systems should target a minimum of 99.99% (4-log) removal of viruses.

4. Legionella				
Source	**Microbial Agent**	**Classification**	**Health Effect**	**EPA Limit**
Water	Legionella	Bacteria	Fever, pneumonia (Legionnaires' disease and Pontiac fever)	0



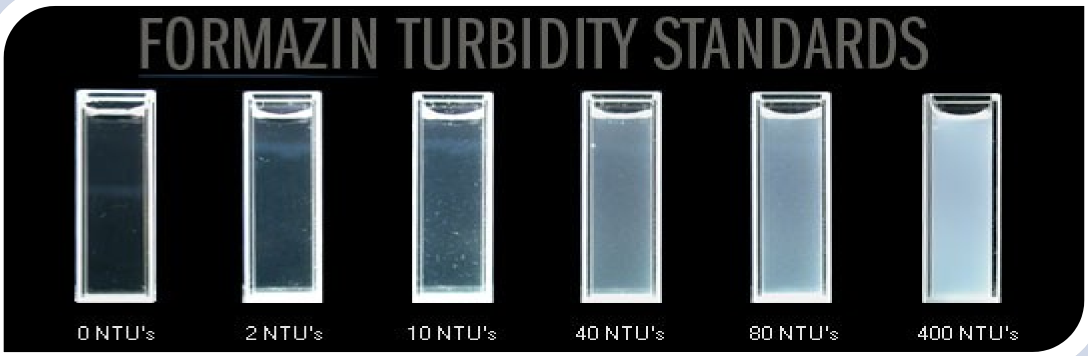
Legionella can permanently live inside of biofilm on the walls of water pipes or tanks.
Source: CDC, National Center for Immunization and Respiratory Diseases, Division of Bacterial Diseases

Legionella bacteria live naturally in aquatic and moist environments, such as lakes, rivers, groundwater, and moist soil. People are exposed to Legionella when they inhale water droplets containing the bacteria (swallowing the bacteria is unlikely to cause illness). Legionella can live in hot water heaters, water storage tanks, pipes with low levels of disinfectant, stagnant pipes, cooling towers, decorative fountains, and hot tubs. Legionella is eliminated through disinfection and frequent flushing and backwashing.

EPA Requirements:
Treatment systems are to include filtration and disinfection. The requirements for the removal of Giardia and viruses will result in adequate control of Legionella.

5. Turbidity

Source	Microbial Agent	Classification	Health Effect	EPA Limit
Various	Various	Various	Various	1 NTU



Example turbidity readings in Nephelometric Turbidity Units (NTU's). On the left is pure water and continuing to the right is progressively dirtier water.
Source: www.waterontheweb.org/under/waterquality/turbidity.html

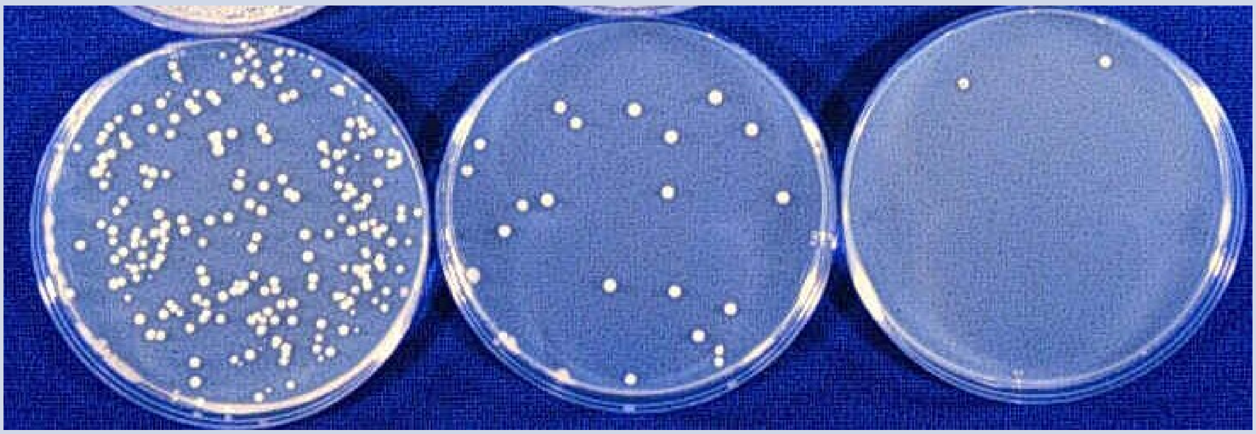
Turbidity is a measure of the cloudiness of water. It is used to indicate water quality, filtration effectiveness, and whether pathogenic organisms are likely to be present. High turbidity levels in drinking water are often associated with high levels of microorganisms, some of which may be pathogenic. Note that most microorganisms found in water are from soil or biofilms and are not harmful. However, these safe microorganisms can provide harbor for more dangerous pathogens.

EPA Requirements:
For systems that use conventional or direct filtration, at no time can turbidity be greater than 1 NTU, and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95 percent of the samples in any month. Systems that use filtration other than conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTUs.

6. Heterotrophic Plate Count

Source	Microbial Agent	Classification	Health Effect	EPA Limit
Various	Various	Bacteria	Various	500

				CFU/ml



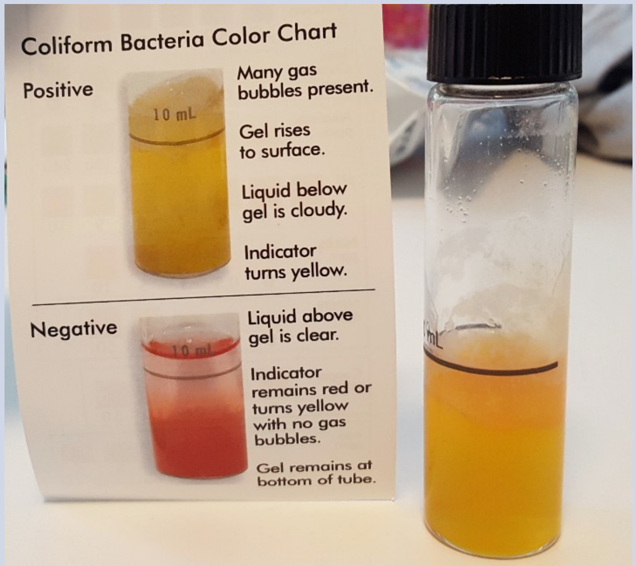
Three heterotrophic plate count (HPC) results. On the left is 150 colony forming units (CFU), in the center is 23 CFU, and on the right is 2 CFU.

Heterotrophic plate count is a test method that counts the number of heterotrophic bacteria colony formations on a standard petri dish with culture media and drinking water. Thus the HPC test (also known as Standard Plate Count) can be used to measure the overall bacteriological quality of drinking water. The lower the number of colonies, the fewer bacteria present in the drinking water. HPC results indicate bacteriological contamination, which is more specific than turbidity readings which indicate general contamination. However, turbidity readings can be taken continuously with analyzers, while HPC tests take anywhere from 2 to 7 days depending on the culture media selected.

EPA Requirements:
No more than 500 CFU per milliliter (CFU/ml). Most drinking water systems achieve less than 10 CFU/ml.

7. Total Coliforms				
Source	**Microbial Agent**	**Classification**	**Health Effect**	**EPA Limit**

Various	Fecal Coliform and E. Coli	Bacteria	Various	5% of samples



Example test for total coliform. A yellow color change indicates that total coliform bacteria are present in the sample, also called total coliform-positive or TC+.

Coliform bacteria live in the intestinal tracts of animals and are generally not harmful to human health. However, a few types of bacteria within the total coliform group, most notably E. coli, can cause serious illness. Coliform bacteria are easily identified during routine water testing and are therefore frequently used as indicators that the water supply may be contaminated. A total coliform test takes 24 hours to provide a reliable result. A fecal coliform test is an acceptable substitute for a total coliform test.

EPA Requirements:
No more than 5 percent of samples can have a total coliform-positive (TC+) result, for each month. For water systems that collect fewer than 40 routine samples per month, no more than one sample can be TC+ per month. Every sample that is TC+ must be analyzed for E. coli. If there are two consecutive TC+ samples, and one is also positive for E.coli, the system has a violation that must be reported by the end of the day.

Engineers are entrusted to design drinking water systems that remove these seven microbial indicators. Each state has additional design requirements related to the removal of biological contaminants. Plus, local health agencies and utilities often have their own, more stringent requirements. EPA, state, and local requirements should be reviewed when designing water system components.

Water Sources and Risks

Having a clean water source that is free of biological contaminants is perhaps the most important factor in preventing water-borne illness outbreaks. The following is a list of water sources is in order of likelihood for biological contamination:

1. Ocean (offshore intake)	Least likely to have biological contamination
2. Deep well	.
3. Rainwater	.
4. Ocean (beach intake)	.
5. Shallow well	.
6. Surface water	.
a. Seepage spring	.
b. River	.
c. Lake	.
d. Canal	.
e. Pond	.
7. Potable water reuse	Most likely to have biological contamination

Each of these water sources is discussed in this Section, as it pertains to potential biological contamination. Keep in mind that the other types of contaminants (physical, chemical, and radiological) also need to be considered when selecting a water source.

Deep Well

Deep wells draw water from underground confined aquifers, which are typically thousands of feet down in the earth. See Figure 8 for an example of a deep well, intermediate well, and surficial (or shallow) well. Raw water from several deep wells is typically pumped through buried pipes to a water treatment plant.

Water from deep in the earth is relatively safe from biological contaminants for the following reasons:

1. Surface contaminants are unlikely to reach down to underground aquifers.
2. The raw water is pumped to the surface under high pressure and thus it remains unlikely for surface contaminants to enter the well casing or piping.
3. Deep well water is typically very cold, which discourages most microorganisms.
4. The well and buried discharge pipe are naturally protected from damage from events such as extreme weather, fires, terrorist acts, crashes, etc.

Deep Well

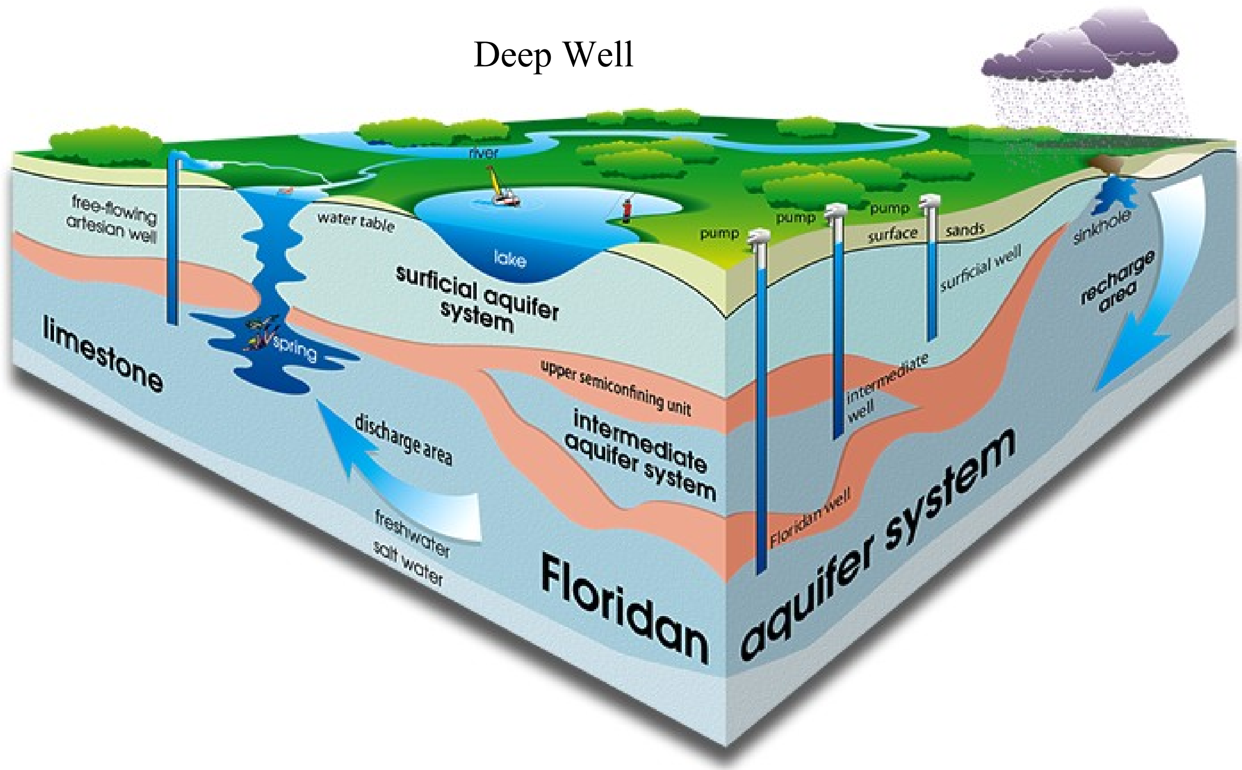


Figure 8: Example of a deep well that draws water from a confined aquifer. The other wells shown are an intermediate well, surficial (or shallow) well, and artesian (or free-flowing) well.

One way to monitor a deep well for potential biological contamination is to check for increases in the total organic carbon (TOC). Surface water typically has a TOC that ranges from 1 to 30 mg/L, while groundwater from a deep well typically has a TOC of less than 1 mg/L. A rise in TOC can indicate that surface waters are someone entering the water supply. See Figure 9 for typical TOC values from different water sources.

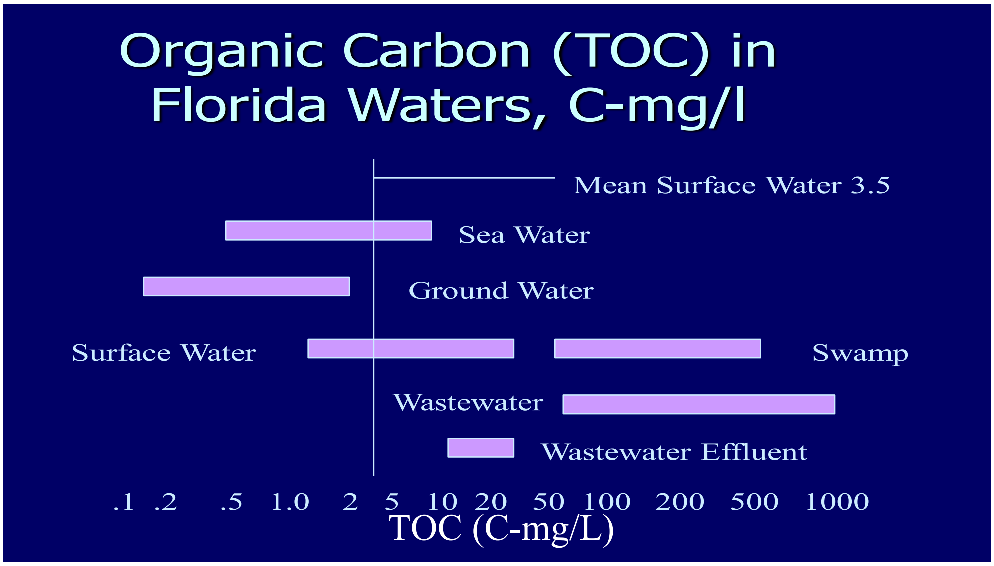


Figure 9: Typical TOC levels for common water types.

<u>Shallow Well</u>

Since ancient times, shallow wells have been recognized as water sources that are generally cleaner than surface water sources such as lakes and rivers. And even today, small shallow wells are common for supplying drinking water to individual houses in rural areas. However, shallow wells are typically more subject to contamination than deep wells, especially in urban areas, as depicted in Figure 10. Also, too many active shallow wells in close proximity will draw down the groundwater table to the point where water shortages occur.

Shallow wells and surface water sources are considered under the direct influent of surface water (UDI). The EPA and most States have additional surface water treatment rules for the design and monitoring of public water systems using surface water or groundwater under the direct influence of surface water. UDI water exhibits either:

- A significant occurrence of algae or large diameter pathogens such as Giardia lamblia or Cryptosporidium, or
- Significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH along with a correlation to climatological or surface water conditions.

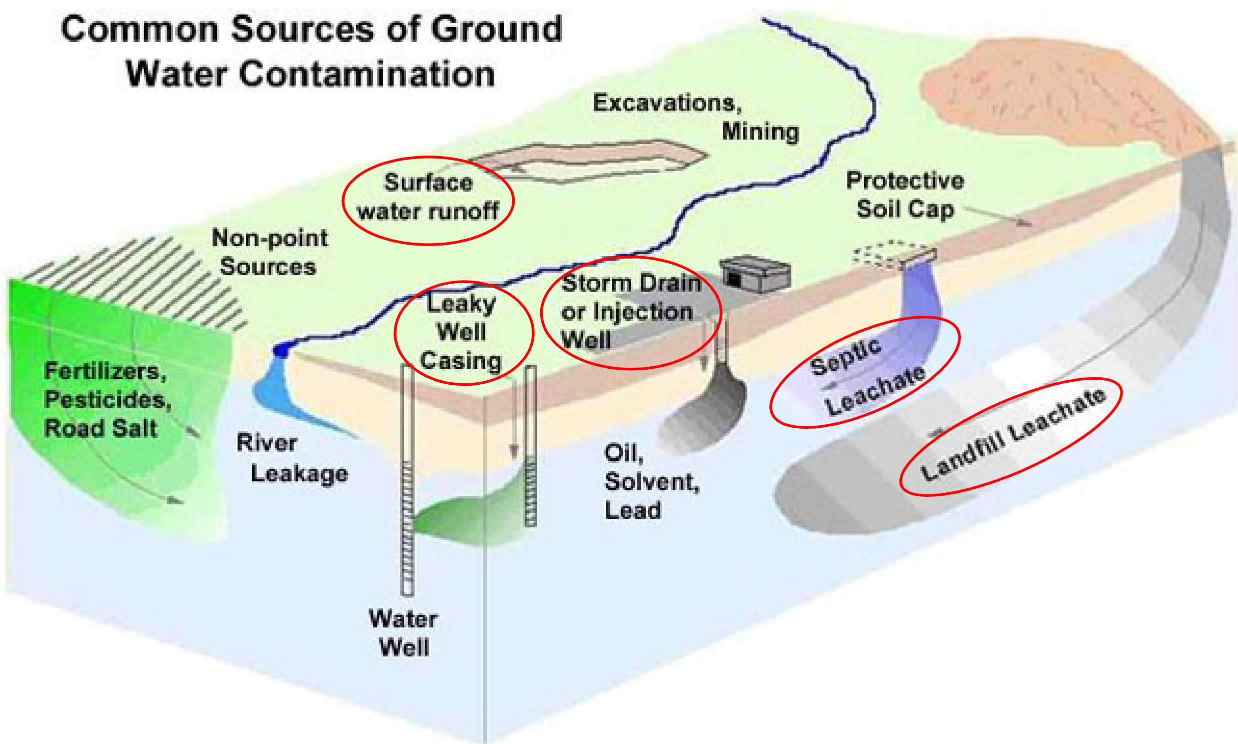


Figure 10: Common sources of groundwater contamination. Sources circled in red have significant biological contaminants that can enter a water well.
Source: Ramanathan, Sharmini. (2009). Management of Contaminated Land - an Overview.

Private residential wells should be kept at a minimum distance of 100 feet from any septic system. Also, the normal groundwater flow should be reviewed and the water well should not be located directly downstream of a nearby septic system.

Surface water

Surface water is the water that collects on the surface of the Earth. This includes springs, lakes, ponds, rivers, canals, and wetlands. In the past, these were the main sources of drinking water. And even today, large lakes and rivers are common water sources for public water systems. For example, Lake Michigan is the source of water for many cities including Chicago. And the Mississippi River is the source of water for many cities including Minneapolis and St. Paul.

Surface waters receive runoff that carries a variety of microorganisms and organics that feed these organisms. A disinfection chemical can be added at the point of water intake to help eliminate pathogens and prevent biofilm growth in the pipeline.

There are two general types of springs:

1. Concentrated/artesian springs. When groundwater flows to the surface under pressure. If protected from surface water, these springs are safer than other surface water sources, and sometimes cleaner than shallow wells. However, the flow capacity is typically insufficient for a public water system.
2. Seepage/gravity springs. These springs contain surface water or shallow groundwater that oozes or seeps from the ground. Seepage springs have a higher likelihood of biological contamination.

Ponds, canals, and wetlands are not good water sources as the level of microorganisms and organics is very high. There is a pond in my backyard, and I tested for the presence of biological contaminants with a Fecal Coliform Test and an HPC Test. The results indicated it is not a safe source for drinking water, as shown in Figure 11.

Figure 11: Pond in the author's backyard (top), Fecal Coliform Test with a positive result, and HPC Test with a count of approximately 100 CMU/ml.

Ocean Seawater

Water in the sea and oceans has a very high concentration of dissolved salts and hence is salty or saline, and undrinkable. The efforts being made to remove salt from seawater and make it fit for drinking and other purposes is known as desalination. This method is very expensive although new technologies have been developed in the 21st Century that are bringing down desalination costs.

Very few pathogens can survive seawater for more than a few hours. When freshwater-based pathogens enter salty water, osmosis draws water out of the cells and thereby inactivates the pathogens. There are algae, bacteria, and viruses that are adapted to survive in seawater, but they typically cannot survive freshwater and it is rare for them to cause illness in humans. An exception is red algae blooms which have neurotoxins that can cause human illness if ingested. See Figure 12 for an example. Oceanographers track algae blooms, and they are predictable to some extent. Water intake pipes should be located to avoid them when possible. Another option is to have multiple intake pipes with significant separation or multiple water sources.

Figure 12: “Red Tide” algae bloom along an ocean beach.

Pathogens that affect humans usually enter the ocean because of poor sanitation practices, runoff that contains human or animal waste, and discharge from ships and boats. If they are ingested before being inactivated by the seawater, they can cause illness. See Figures 13 and 14 for examples.

Figure 13: An example of an intercoastal port releasing brackish water into the ocean during low tide. The brackish water contains surface water from urban runoff, canals, rivers, and other sources that contain biological contaminants.

Figure 14: A blackwater release from a ship, seen in brown.

To avoid the high level of contaminants along the shoreline, water intake pipelines are often routed far out into the ocean See Figure 15 for an example of an offshore intake arrangement.

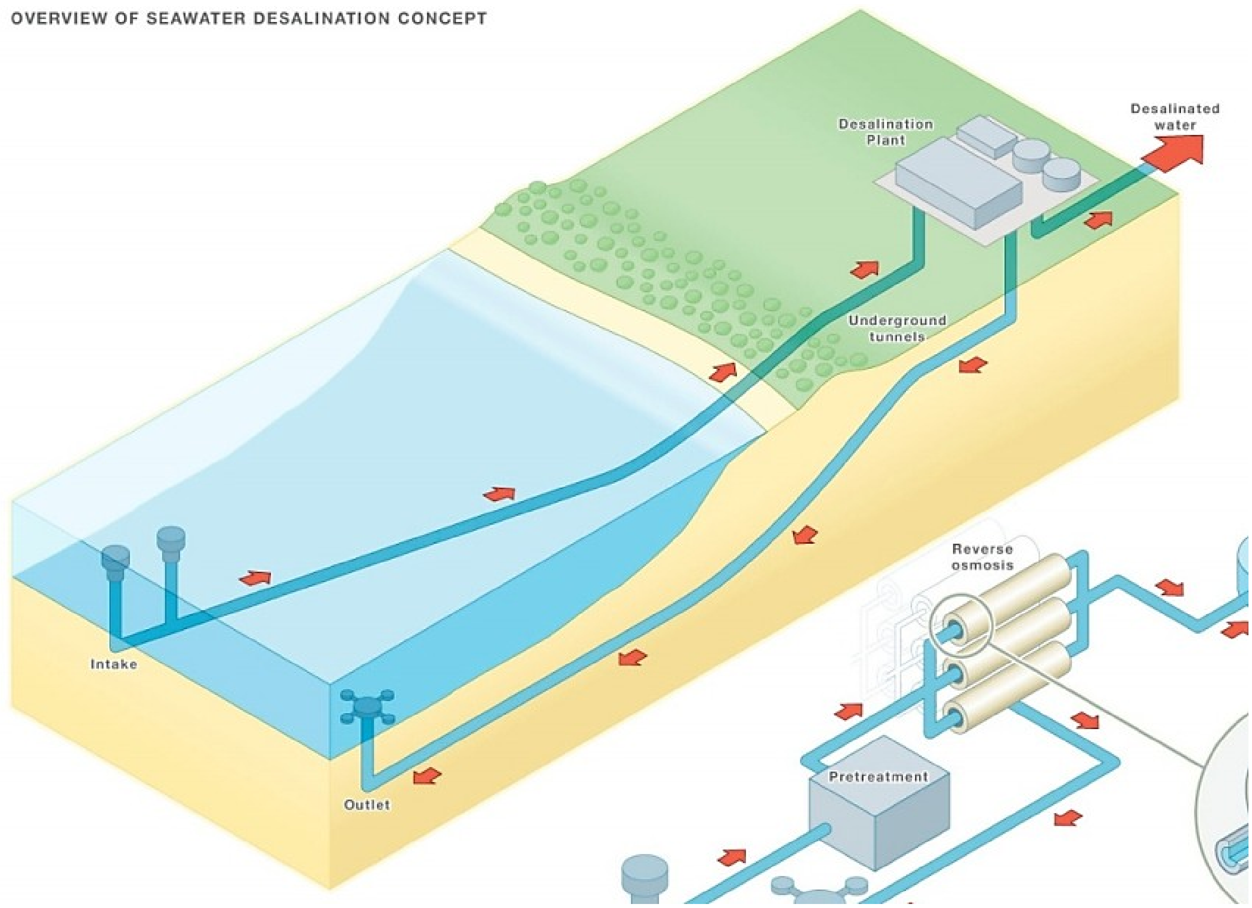


Figure 15: Example of an offshore intake pipe.
Source: http://victoriasdesalinationplant.blogspot.com.au/

Another option is to place intake wells near the shore and utilize the sand along the coast to filter the ocean water. See Figure 16 for an example of a beach intake well.

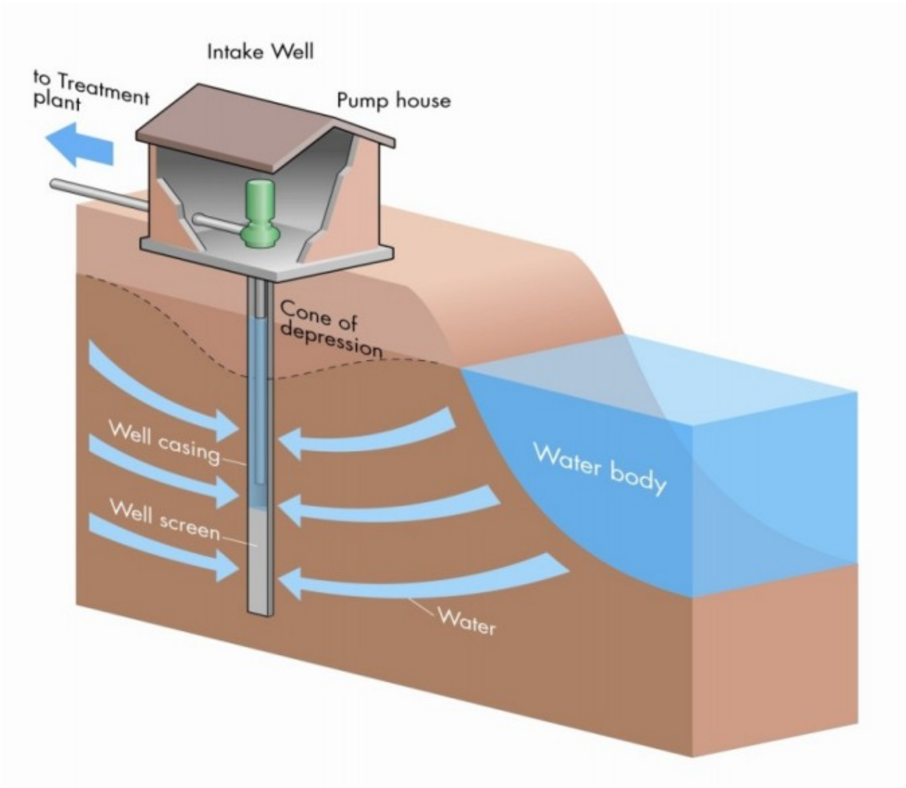


Figure 16: Example of a beach intake well
Source: Water Globe Consulting

<u>Rainwater</u>
The main source of natural water on Earth is rain. When it first drops from the clouds, this is a pure form of water. However, while falling to the Earth, rainwater gets polluted with dust particles and some dissolved gases. Then, the rainwater needs to be collected and stored (see Figure 17), and this introduces many opportunities for biological contamination. For these and other reasons, rainwater is rarely used as a water source for public drinking water systems.

Figure 17: Example of a rainwater storage tank.
Source: Aheeyar, Mohamed & Bandara, M.. (2010). Economic Evaluation of Institutional Level Rainwater Harvesting.

Potable Water Reuse

It is common to reclaim treated wastewater for irrigation, agriculture, cooling water, various urban uses (often in purple pipes), wetlands, recharging groundwater, and augmentation of surface waters. Recently, treated wastewater has been used for drinking water as well.

The process of using treated wastewater for drinking water is called potable water reuse. There are two types of potable water reuse:

1. *Indirect potable reuse:* Uses an environmental buffer, such as a lake, river, or groundwater aquifer, before the water is treated and distributed.
2. *Direct potable reuse:* Involves the treatment and distribution of wastewater without an environmental buffer.

Indirect potable reuse is relatively common. Many utilities draw water from a lake, river, or aquifer that also receives treated wastewater effluent. These systems require regular monitoring to ensure the environmental buffer remains stable so there is no breakthrough of wastewater directly into the water intake.

Direct potable reuse is a relatively new concept that is made possible by advanced technology, such as reverse osmosis. The main concern is that fecal pathogens present in wastewater will survive the treatment process and contaminate the drinking water. Although the wastewater is disinfected, there is no guarantee that 100 percent of the pathogens have been inactivated. Hence the water treatment system needs to reliably remove microorganisms to a greater extent than with other water sources. State requirements vary, but some states require a 99.9999999999% (12 log) removal of viruses for direct potable reuse. See Figure 18 for an example.

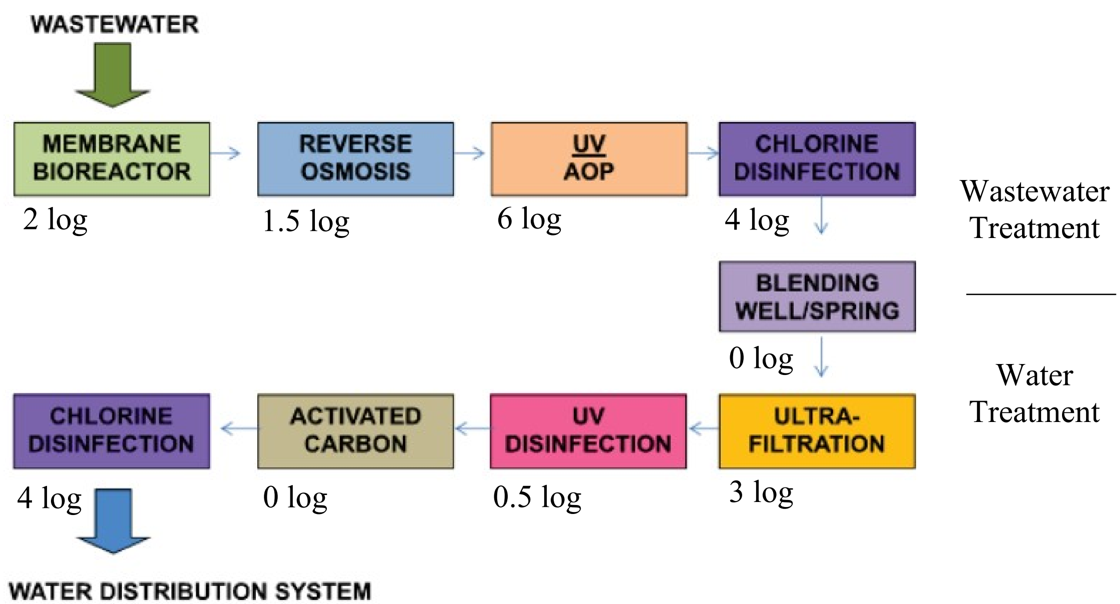


Figure 18: Example flow diagram for a direct potable reuse system, with the wastewater treatment processes at the top and water treatment processes at the bottom. AOP stands for Advanced Oxidation Process. The log removal of viruses is stated for each process, with a total of 21 log removal.

Source: D. Venable, E. Livingston, J. Vandegrift. (2017) Village of Cloudcroft PURe Water Project.

Water Treatment and Disinfection

Each water treatment plant is comprised of a unique combination of treatment processes. Most treatment processes eliminate some amount of microorganisms from the water, even if that isn't the main purpose of the treatment process. These processes can provide reduction credits for attaining compliance with the log reduction requirements of *Crypto* (2-log), *Giardia* (3-log), and viruses (4-log), as shown in Table 1. For example, conventional sand filtration provides a 2-log credit, provided the effluent has a turbidity of less than 0.3 ntu (95% monthly average) and 1.0 ntu (maximum).

Table 1: Turbidity Requirements and Log Reduction Credits for Typical Treatment Processes, per the Federal Surface Water Treatment Rule.

FILTRATION TREATMENT TECHNOLOGY	COMBINED FILTER EFFLUENT (CFE) TURBIDITY (95% MNTHLY/MAX) ntu	MAXIMUM LOGS OF CREDIT FOR PHYSICAL REMOVAL		
		Cryptosporidium	*Giardia*	Viruses
Conventional	*** 0.3/1	>2	2.5	2.0
Direct	***0.3/1	>2	2.0	1.0
Slow Sand	1/5	>2	2.0	2.0
Diatomaceous Earth	1/5	>2	2.0	1.0
Reverse Osmosis	0.3/1	>2	>3.0	3.0
Nanofiltration	0.3/1	>2	>3.0	3.0
Ultrafiltration	0.3/1	>2	>3.0	0
Microfiltration	0.3/1	>2	>3.0	0
Pretreatment plus Bag or Cartridge (B/C) *	1/5	2	2.0	0
Conventional Filtration followed by (B/C)	0.5/5	2	2.5	2.0

The main method for removing pathogens is disinfection. Disinfection is typically the last treatment process before the finished water is sent to storage tanks and distribution. The following are common disinfection methods:

1. Free Chlorine
2. Chloramines
3. Chlorine Dioxide
4. Ozone
5. UV

The following table provides advantages and disadvantages for each disinfection method.

Table 2: Comparison of Disinfection Alternatives		
Alternative	Advantages	Disadvantages
Free Chlorine	• Most common approach • Longest track record • Low contact time required • Low cost	• Residual drops in distribution system, resulting in biofilm • Forms regulated disinfection by-products (DBPs)
Chloramines	• Maintains stable residual in large distribution systems • Minimizes trihalomethane (THM) and halogenic acetic acids (HAA) formation • Controls DBP production • Fewer taste and odor complaints than chlorine • Ability to penetrate biofilms	• Nitrification potential • May form non-regulated DBPs such as NDMA (N-nitrosodimethylamine) • Increased elastomer degradation • May require a corrosion inhibitor if lead pipes present. • Health effects with sensitive customers • Some industrial process impacts • Need multiple injection points (chlorine and ammonia)
Chlorine Dioxide	• Does not form THMs or HAAs	• Possible odor issue if residual is not controlled

	• Low contact time required • Effective *Cryptosporidium* inactivation	• Forms chlorite, requiring additional monitoring • High cost
Ozone	• Removes volatile organic compounds (VOCs) and synthetic organic compounds (SOCs) • Effective *Cryptosporidium* inactivation	• Provides no residual in the distribution system • May form bromate • High cost
UV	• Effective *Cryptosporidium* inactivation	• Provides no residual in the distribution system

Free chlorines (chlorination) and chloramines (chloramination) are by far the most common types of disinfection for public water systems, and so it is important for water engineers to have a basic understanding of each.

- *Chlorination* typically refers to the addition of chlorine to achieve a residual (or free) chlorine in the water which reacts and inactivates microorganisms.
- *Chloramination* refers to the addition of chlorine and ammonia to create a residual concentration of monochloramine, NH_2Cl, which reacts and inactivates microorganisms.

In both methods, it is important to achieve the proper concentration of chlorine. Refer to Figure 19 for a typical chlorination curve. Chlorination is when sufficient chlorine is added to form free chlorine (see the right of the curve). Typically, the free chlorine must be maintained between 0.2 and 4.0 mg/L. Chloramination is when the ratio of chlorine to ammonia is maintained to maximize the concentration of monochloramine (see the zone in red). In this case, combined chlorine is measured (instead of free chlorine) and must be maintained between 0.6 and 4.0 mg/L.

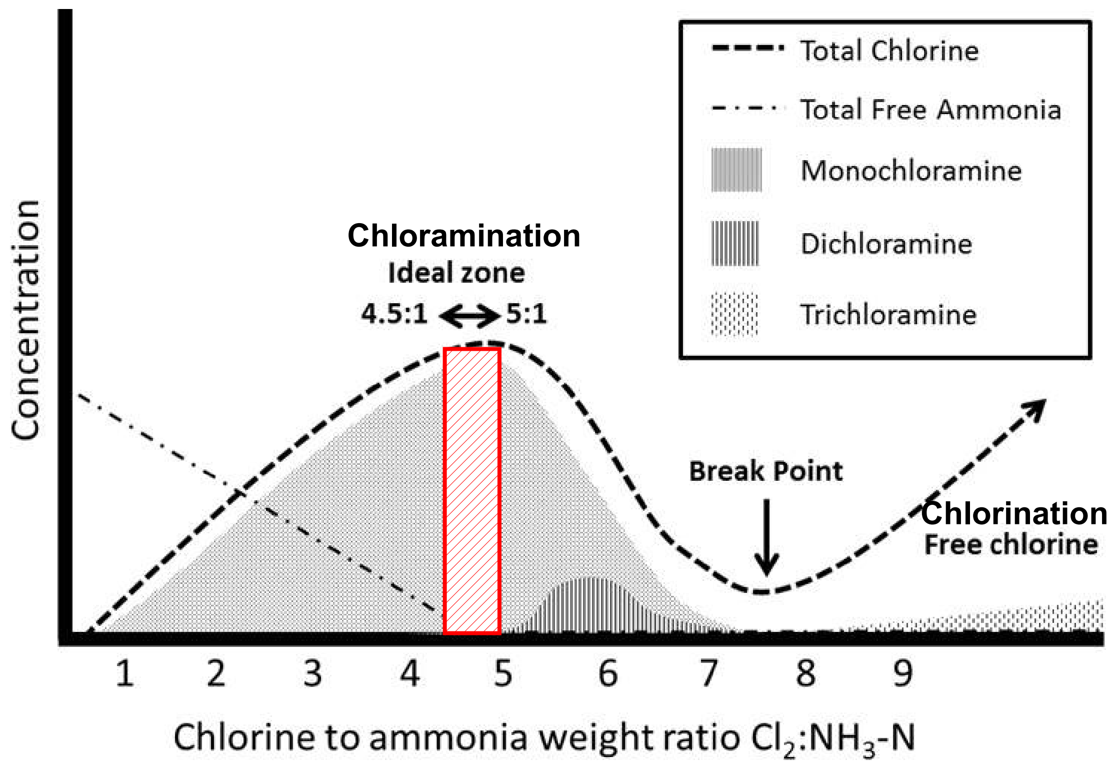


Figure 19: Breakpoint chlorination curve with the ideal zone in red for achieving maximum monochloramine formation while also minimizing free ammonia. In practice, a ratio range of 3:1 to 5:1 is often utilized.
Source: Health Canada. (2019) Chloramines in Drinking Water.

Recently, many public water systems have switched to chloramination in the distribution system to overcome issues associated with regulated DBP formation, such as THMs and HAAs. It is also common to use a combination of chlorination and chloramination for systems achieving a 4-log (or greater) reduction in viruses. Chlorine is first added in a high concentration for the required contact time to achieve the 4-log reduction with free chlorine (chlorination). Then, ammonia is added to give a ratio of chlorine to ammonia between 3:1 to 5:1, which results in chloramines being maintained in the distribution system (chloramination). Such systems require several free and total chlorine analyzers taking regular readings, which are used to adjust the chlorine and ammonia feed rates, and to reporting compliance.

Log Removal

The level of inactivation or removal of microorganisms is customarily measured on a log scale, as a convenience to avoid long numbers. An easy way to remember the correlation between log number and percent removal is that the log number equals the number of 9's in the percent removal. So, 1-log removal is 90%. And 6-log removal is 99.9999%.

The Federal Surface Water Treatment Rule developed by the US EPA, which applies to surface water and shallow well water sources, requires the following removal rates:

- *Crypto*: 2-log (99%)
- *Giardia*: 3-log (99.9%)
- Viruses: 4-log (99.99%)

Many public water systems use deep well water sources that are not required to follow the Surface Water Treatment Rule. However, many utilities choose to follow the Rule out of their own volition, including providing 4-log virus removal, for one or more of the following reasons:

- To avoid having to conduct source water and finish water assessments.
- As corrective action for a fecal contaminated groundwater source.
- As corrective action for a significant deficiency involving positive test(s) for fecal coliform.
- To be proactive in preventing violations and outbreaks.

Contact Time

Determining the removal rate of a disinfection system involves calculating the contact time (CT) and comparing it to the required contact times listed in the EPA Surface Water Guidance Manual. Contact time is calculated as follows:

Step 1: Determine the time available in the basin at peak flow. Multiply the storage volume by the baffling factor (see EPA Table 3-2 on the next page) and divide by the peak hourly flow.

$$\text{Time (min)} = ¿ \frac{\text{Volume}\,(\text{gal}) \times \text{Baffling Factor}}{\text{Peak Hourly Flow (gpm)}}$$

Step 2: Determine the contact time available at peak flow. Multiply the Time (from Step 1) by the chlorine concentration at peak hourly flow.

$$CT_{avail}\ (\text{min mg/L}) = \text{Time (min)} \times \text{Chlorine Conc (mg/L)}$$

Step 3: Find the required contact time (CT_{req}) from the EPA Tables (see Table B-2 on the following page) using the pH, temperature, and chlorine concentration.

Step 4: Determine if the disinfection system meets the EPA requirements. Compare CT_{avail} to CT_{req}. If CT_{avail} is greater, then the disinfection system met the contact time requirements. If CT_{avail} is less, consider increasing the storage volume or increase the disinfectant concentration, and recalculating.

Table 3-2 – Baffling Factors

Factor	Description
0.1	None, agitated basis, very low length to width ratio, high inlet and outlet flow velocities. Enclosed circular or rectangular tank with single inlet and outlet line. Enclosed circular or rectangular tank with inlet on top and outlet on the bottom, either directly below or on the same side as the inlet line.
0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles. Enclosed circular or rectangular tank with inlet on top and outlet on the bottom on the opposite wall.
0.5	Baffled inlet or outlet with some intra-basin baffles.
0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders.
1	Very high length to width ratio (pipeline flow), perforated inlet, outlet, and intra-basin baffles.

Table B-2 – CTreq values for 4-log virus inactivation of viruses by free chlorine in mg/L•min

Temperature (°C)	pH	
	6-9	**10**
0.5	12	90
5	8	60
10	6	45
15	4	30
20	3	22
25	2	15

Example 1: Engineer Vicki has been asked to size a water pipe for 4-log treatment. Sodium hypochlorite will be injected to achieve a free chlorine concentration of 4 mg/L. The distance available is 100 feet, as shown in Figure E1. The peak hourly flow is 2000 gpm, pH is 8, and temperature 20º C. What is an economical pipe size that meets the EPA requirements for 4-log virus inactivation?

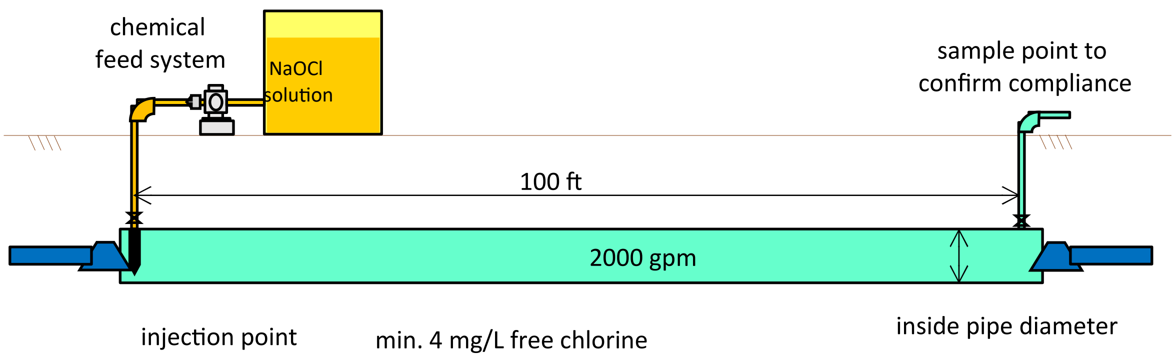


Figure E1: Conceptual profile of 4-log system for Example 1.

Solution: Vicki uses an iterative process to calculate the contact time for different common pipe sizes, then chooses the smallest acceptable pipe diameter.

First, she tries a diameter of **24 in** (2 ft):

Step 1: Baffling Factor of 1.0, per Table 3.2

$$\text{Time} = ¿ \frac{100\text{ ft} \times \pi\left(\frac{2\,ft}{2}\right)^2 \times 1.0}{2{,}000\text{ gpm} \div 7.48\text{ gal}/ft^3} = 1.17\,min$$

Step 2: $\text{CT avail} = 1.17\ \text{min} \times 4\ \text{mg/L} = 4.7\ \text{min mg/L}$

Step 3: CTreq of 3 min mg/L (does not depend on diameter)

Step 4: $\text{CT avail of } 4.7\text{ min mg/L} > 3\text{ min mg/L}$ (acceptable)

Next, she tries a diameter of **20 in** (1.67 ft):

$$\text{CT avail} = \frac{100\text{ ft} \times \pi\left(\frac{1.67\,ft}{2}\right)^2 \times 1.0}{2{,}000\text{ gpm} \div 7.48\text{ gal}/ft^3} \times 4\text{ mg/L} = 3.3\ \text{min mg/L} > 3 \quad (\text{acceptable})$$

And finally a diameter of **16 in** (1.33 ft):

$$CT\,avail = \frac{100\text{ ft} \times \pi\left(\frac{1.33\,ft}{2}\right)^2 \times 1.0}{2{,}000\text{ gpm} \div 7.48\text{ gal}/ft^3} \times 4\text{ mg/L} = 2.1\ \text{min mg/L} < 3 \quad (\text{not acceptable})$$

Vicki chooses a pipe diameter of **20 inches**, which is the smallest common pipe size that meets the contact time requirements for 4-log treatment.

Distribution System Approaches

The distribution system should efficiently transfer the treated water to each customer service line without introducing biological contamination. See Figure 20 for an example of a distribution system.

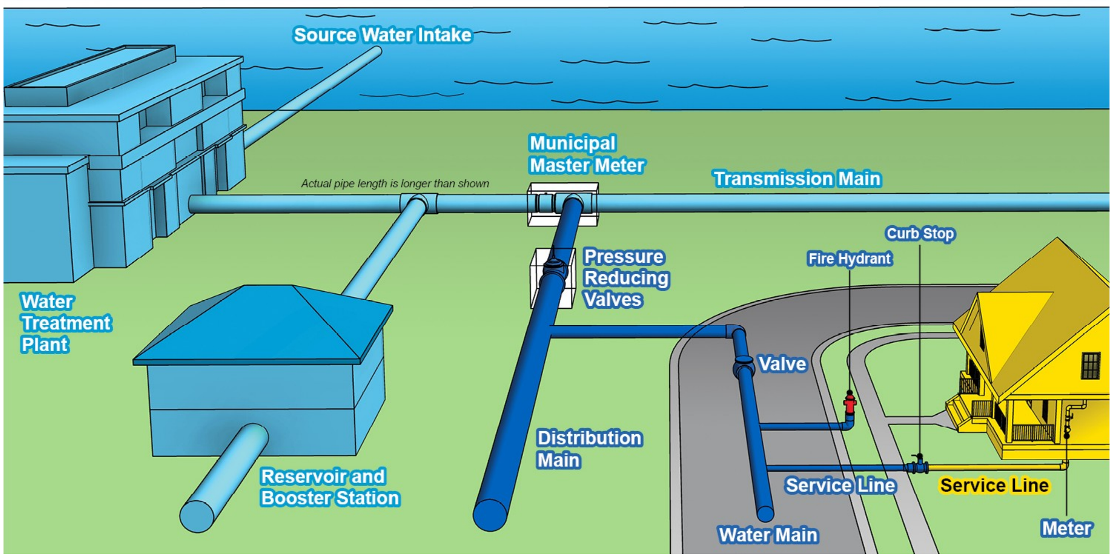


Figure 20: Example distributions system with pipes in shades of blue. The system starts with the transmission main pipe leaving the water treatment plant and ends at each service line at the property line.
Source: Great Lakes Water Authority

Potential sources of biological contamination in a distribution system are as follows:

- Cross-connections to contaminated waters such as wastewater or stormwater pipe connections.
- Inadequate backflow prevention.
- Stagnant or old water in pipes or storage tanks.
- Low disinfectant residual and nitrification.
- Biofilm growth with inadequate flushing and chlorine burns.
- Low pressure in combination with pipe leaks.
- Purposeful contamination by assailants.

Cross-connections

Connections between the water distribution system and any wastewater or stormwater system are called *cross-connections*. These are typically prohibited without an air gap. For example, Erik is an engineer designing a wastewater wet well, and operations staff requested a water flushing system for periodic cleaning of the well. Erik recognizes that routing the line inside the wet well with spray nozzles would not provide an air gap as the nozzles could come in direct contact with the wastewater. Instead, Erik designs for the water line to end above grade near the wet well with a hose connection fitting. He also includes a backflow preventer in the above-ground pipe to comply with state requirements.

Erik explains to operations staff that a spray nozzle system cannot be directly connected because of the potential for pathogens to enter the community drinking water system. If a spray nozzle system is desired, a different water source should be used, such as reclaimed water. Another alternative would be to use a water tank with an air gap and a pump to deliver high-pressure water to the nozzles.

Backflow Prevention

Backflow preventers provide a reliable form of protection near the point of use. See Figure 21 for common connections that require a backflow preventer. There are several different types of backflow preventers. Check state regulations for the particular type of backflow preventer required for each application.

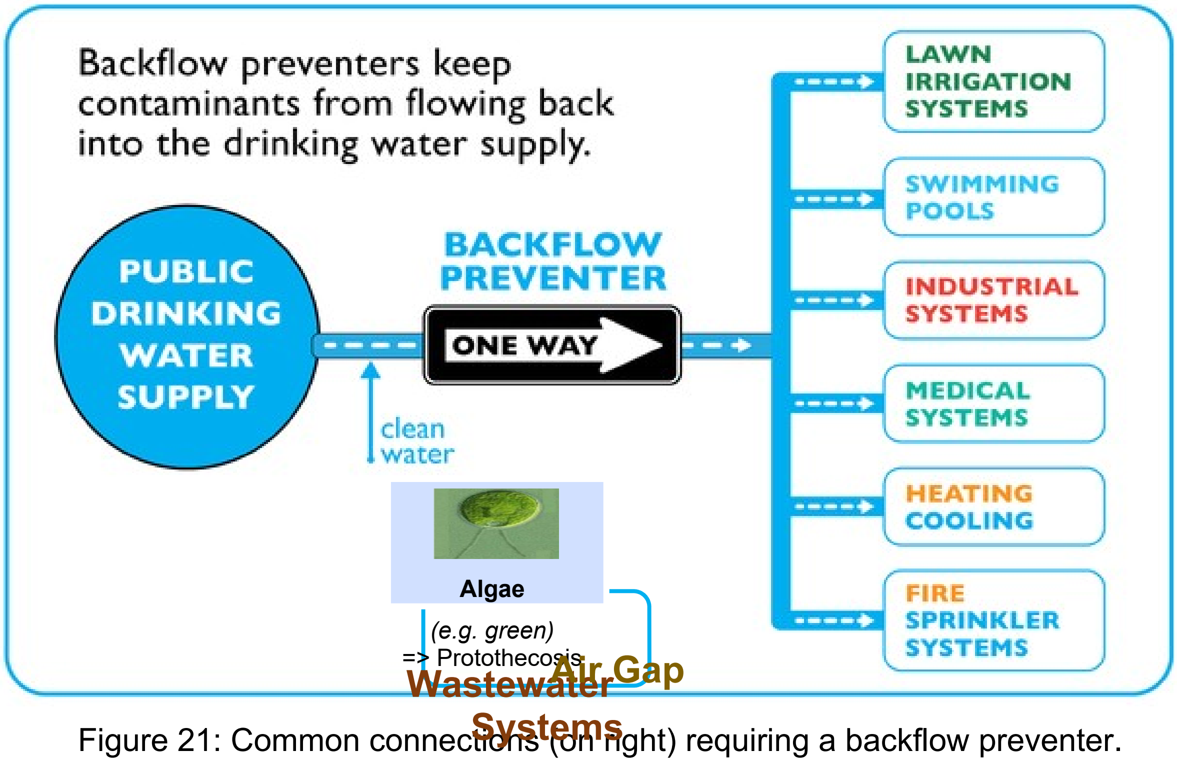


Figure 21: Common connections (on right) requiring a backflow preventer.

<u>Biofilm</u>

Biofilm is another potential source of biological contamination. Maintaining the required disinfectant residual is the most important step to prevent and contain biofilm. However, with time bacteria will find weak spots in the system and begin to grow colonies. Colonies grow on surfaces such as pipe walls and produce a slime layer which aids in protecting the microorganisms from the disinfectant and high-velocity water. See Figure 22.

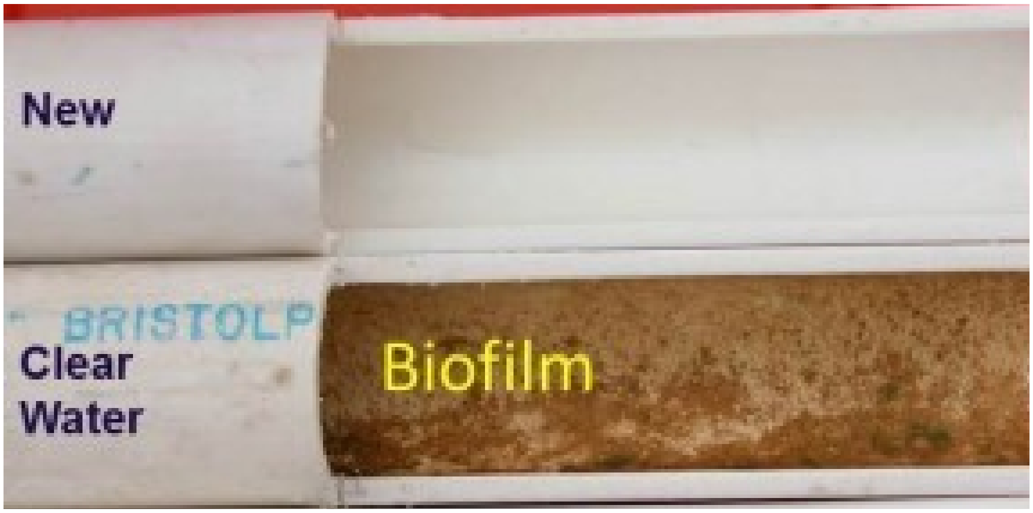


Figure 22: Brand new small PVC pipe (top) and pipe that was in service with brown biofilm growth (bottom).
Source: Peter Konjoian from Konjoian's Greenhouses

Occasionally the biomass will break off the surface and disperse to other areas of the distribution system, as shown in Figure 23. Bacteria that grow as biofilm are not pathogens and only cause illness if a large quantity is swallowed. However, the biofilm can provide a harbor for pathogens that would otherwise be inactivated by the disinfectant residual. And biofilm can result in the following water quality issues:

- Leads to nitrification
- Increases turbidity and HPC test results
- Converts inorganics to organics (TOC rises)
- The increase in organics lead to DBP formation
- Causes pH fluctuations
- Produces hydrogen sulfide

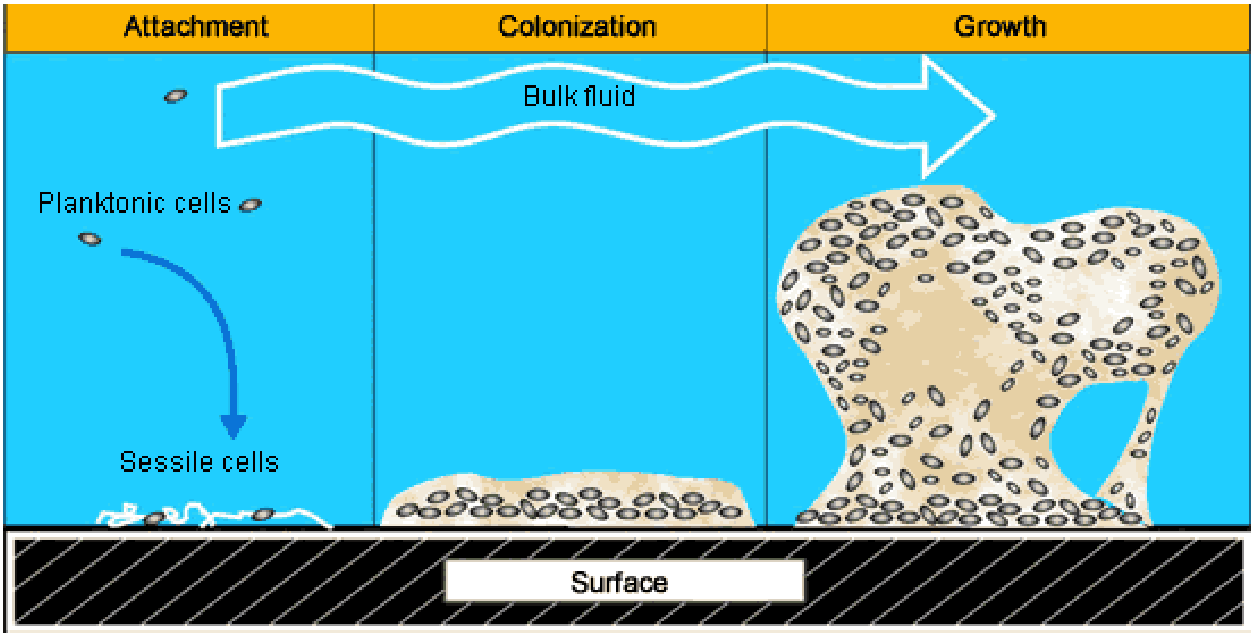


Figure 23: Depiction of the stages of growth of bacterial biofilm.
Source: Kashef, Nasim & Huang, Ying-Ying & Hamblin, Michael. (2017). Advances in antimicrobial photodynamic inactivation at the nanoscale. Nanophotonics. 6. 10.1515/nanoph-2016-0189.

Controlling biofilm is often considered the responsibility of operations and maintenance staff. For example, water lines are frequently flushed and free chlorine levels are increased (chlorine burn) for a few days every 6 months. However, the engineering of distribution system components has a big impact on being able to control biofilm. The following is a list of design approaches that can reduce biofilm:

- Avoid dead-ends in the piping.
    - For cul-de-sacs, consider looping the water main or continuing it to a nearby street with an easement.
    - For bypass lines, design a small pipe around the closed isolation valve with a valve cracked open to allow a small amount of flow at all times.
- Avoid oversizing water pipes:
    - Velocities at maximum daily demand should exceed 3 ft/s (1 m/s).
    - Average velocities below 1 ft/s (0.3 m/s) should be avoided if possible.
- Provide an abundance of flushing locations. Check if fire hydrants will be used for flushing.
- Install automatic flushing devices at stagnant, low flow, or dead-end areas.
- Provide isolation valves at all branches and regularly spaced on long pipelines.
- Choose pipe materials and linings that deter biofilm growth.

- Include mixing systems in water storage tanks.
- Reduce nutrient levels in the water, which cuts off the biofilm food supply.
- Consider switching from chlorine to chloramine disinfection.
- For remote areas of the distribution system, consider adding a booster pump and disinfection feed system to maintain flow circulation and disinfection levels.
- Provide water quality monitoring instrumentation.

Pipe Material and Coating

Multiple studies have shown that biofilm grows more slowly on plastic pipes (PVC and PE) and more rapidly on ductile iron and steel pipes. However, not all studies agree on this conclusion and it appears the difference is not significant. Recently, antimicrobial water piping has been introduced as an alternative pipe material for water distribution system piping. Such piping actively prevents biofilm. An example is Microban pipe from K-Wasser.

Another recent development is to coat the inside of water pipes with an antimicrobial lining. An example is d2p 9700 Masterbatch. Antimicrobial coating products have been on the market for decades; however, it is only recently that they have been developed with reduced toxicity for use with potable water. The design engineer should confirm that the selected pipe and liner products have NSF 60/61 approval for drinking water applications.

Surface Disinfection

Anytime that changes are made to water system components, all wetted surfaces are to be disinfected prior to the new components being placed into service. This prevents pathogens from entering directly into the water system. Most states require adhering to the following AWWA standards for surface disinfection:

- AWWA C651 - Disinfecting Water Mains
- AWWA C652 - Disinfection of Water Storage Facilities
- AWWA C653 - Disinfection of Water Treatment Plants
- AWWA C654 - Disinfection of Wells

Water Storage Tank Approaches

Water storage tanks are in nearly every water distribution system. Tank types include ground storage tanks, elevated storage tanks (also called water towers), and standpipes. See Figures 24 and 25 for a typical ground storage tank.

Figure 24: Ground storage tank of concrete construction.

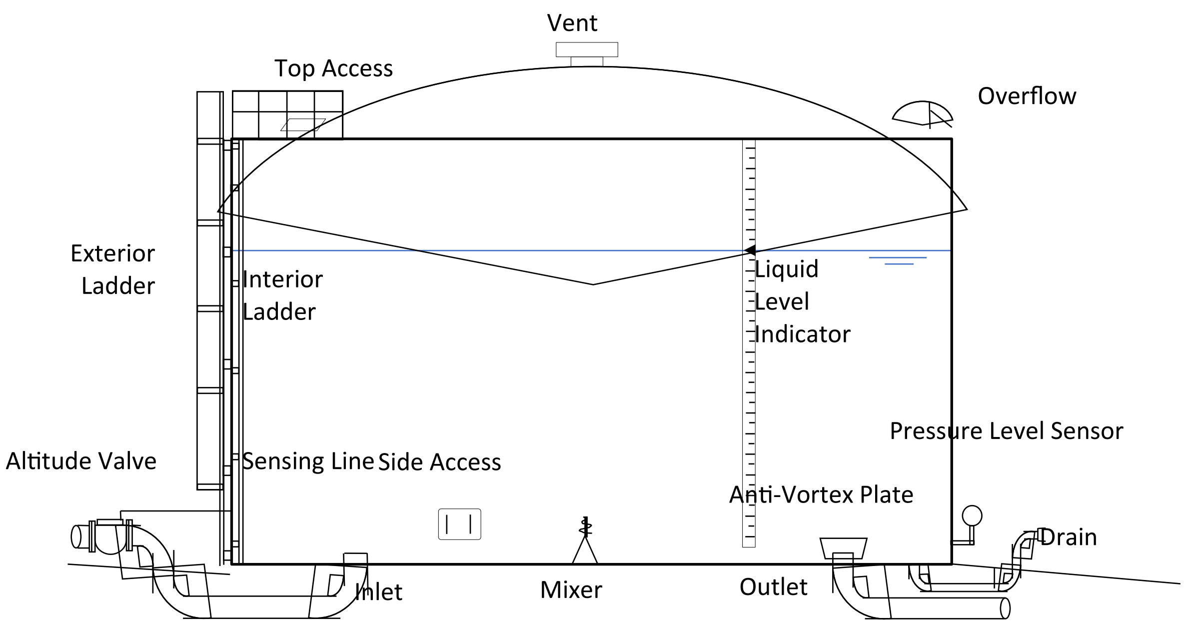


Figure 25: A ground storage tank with labels for typical tank features.

In recent decades, there has been a growing concern for water quality deterioration resulting from microbial growth in storage tanks. Excessive water age is considered the most important factor related to water quality deterioration. A long detention time (more than 24 hours) results in “old water” which is more susceptible to low disinfectant levels and microbial growth. Distribution systems with remote storage tanks are more prone to water age problems in the most distant tanks. Operational changes can reduce water age to acceptable levels, such as by operating the tank at a lower water level.

Thermal stratification and poor mixing can result in excessive water age in certain zones within the tank. This can be prevented with a tank mixing system. A computational fluid dynamics (CFD) model may help indicate if a mixing system is required, as well as helping to select the best mixing system design. Types of mixing systems include hanging curtains, baffle walls, mechanical mixers, passive mixing systems, and aeration systems. See Figure 26 for an example of a tank mixing system.

Figure 26: A passive mixing system with several nozzles that are spaced and oriented to mix the entire tank contents.

A water storage tank must be an enclosed and sealed structure, with fine mesh insect screens on the overflows and vents. Even so, storage tanks are susceptible to contamination from external debris and biological material. For example, a tank may develop cracks or be damaged, which results in openings. There are many cases of creatures such as mice or rats entering storage tanks, dying in the water, and water quality tests giving positive coliform test results.

Engineers can help prevent biological contamination by designing for the following:

- The tank structure is to be structural sound with plenty of safety factor for all dead and live load combinations,
- Keep the tank above ground to avoid surface water and groundwater penetration,
- Include a mixing system to prevent thermal stratification and dead zones,
- Specify long-lasting screens at openings,
- Ensure overflows and drainpipes discharge above grade and are not directly connected to sewers,
- Ensure interfacings and penetrations are robustly sealed for longevity,
- Design for two or more tanks when possible so that any tank can be taken out of service at any time (see Figure 27).

Figure 27: Two ground storage tanks in parallel. Either tank can be taken out of service while the other tank provides the minimum required storage volume.

To help identify potential contamination or structural problems, tanks are to be inspected regularly to review wall penetrations, hatches, vents, overflows, roofs, and walls. Per NFPA 25, tank interiors must be inspected every 3 years for steel tanks without corrosion protection, and every 5 years for all other tanks. Engineers should review the inspection results to help determine the need for rehabilitation before problems occur.

The following maintenance tasks help control microbial growth in storage tanks:

- Regular draining and cleaning,
- Regular chlorination (free chlorine burn),
- Regular inspections (diving with a camera if necessary), and
- Periodically lower the water level so at least 2/3 of the tank is turned over daily.

Helpful References

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Federal Regulations:

EPA Drinking Water Regulations:
https://www.epa.gov/dwreginfo/drinking-water-regulations

Surface Water Treatment Rules:
https://www.epa.gov/dwreginfo/surface-water-treatment-rules

Ground Water Rules:
https://www.epa.gov/dwreginfo/ground-water-rule

National Primary Drinking Water Regulations:
https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

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AWWA (2013) "Disinfection of Wells", AWWA Standard C654.

