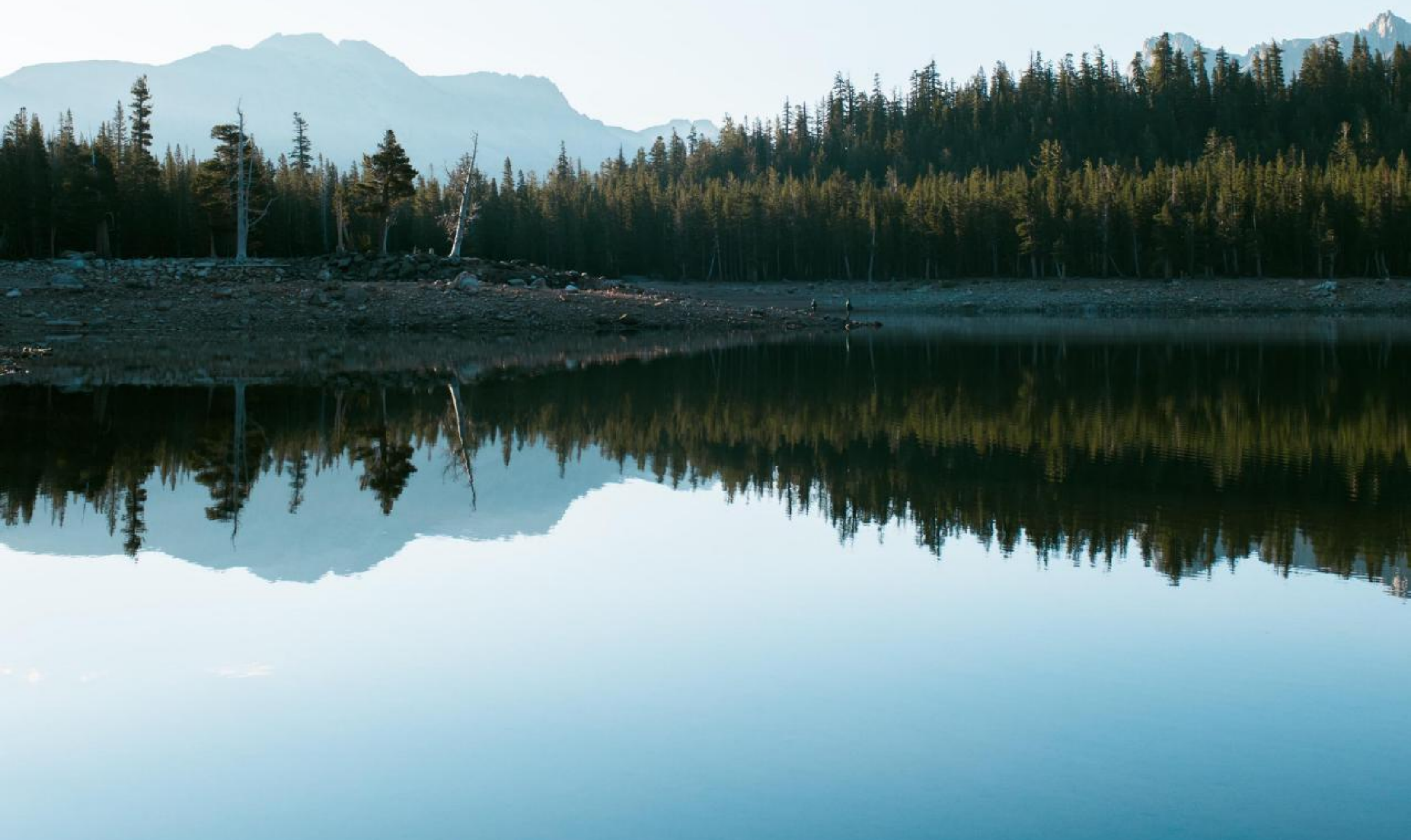
Water Treatment Plant Operation Processes I



ZERO TEXTBOOK COST

WATER-150

WATER TREATMENT PLANT OPERATION PROCESSES I

An Open Educational Resources Publication by College of the Canyons

Created by Vincent Titiriga

Editors: Alexa Johnson & Alex Gavilan
Cover: Ian Joslin

Version 1.4

2020

Acknowledgements

College of the Canyons would like to extend appreciation to the following people and organizations for allowing this textbook to be created:

California Community Colleges Chancellor's Office
Chancellor Dianne G. Van Hook
Santa Clarita Community College District
College of the Canyons Distance Learning Office

Table of Contents

CHAPTER 1 – SOURCE WATER

Supplying water to the public is an extremely important function in society because water is the basic building block of life. Because water quality is of the utmost importance, new regulations and water quality standards are continually changing and evolving to make sure the public has safe sources of drinking water.

After reading this chapter, you should be able to:

- describe processes in the hydrologic cycle;
- identify sources of groundwater and surface water; and
- apply unit conversions and solve math problems involving area

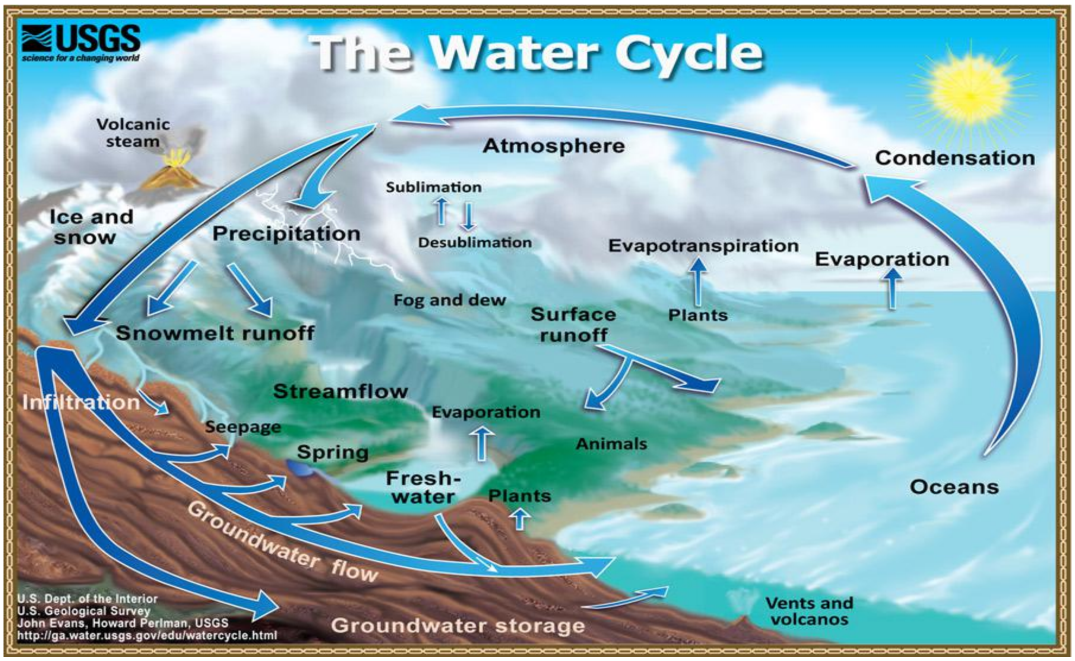


Figure 1.1: The Hydrologic Cycle[1]

The **hydrologic cycle** is the continual movement of water on the surface of the planet. The water moves above, below, and across the Earth's surface as a liquid, gas, or solid. Nine key elements of the hydrologic cycle are defined as follows:

1. **evaporation** – the process in which water moves from a liquid to a gas state
2. **transpiration** – the process in which water moves from a liquid to a gas state from plants
3. **condensation** – the process in which water moves from a gas to a liquid state
4. **precipitation** – the process in which water falls from the sky as rain, snow, sleet or hail
5. **Infiltration** – the process in which liquid water soaks into the ground; also known as percolation

[1] The Water Cycle by the USGS is in the public domain.

6. **subsurface Flow** – the process in which water in the liquid state flows below the Earth's surface. The movement is generated by gravity and obstructions below the surface of the Earth.
7. **runoff** – the process in which water in the liquid form travels to bodies of water.
8. **water storage** - water is naturally stored in liquid form in lakes, ponds, wetlands, and groundwater aquifers. In solid form water is naturally stored in ice, snow, and glaciers. This natural storage provides much of the water treated for human consumption.
9. **snowmelt** – the process through which water as a solid converts to a liquid; in California, snowpack is a critical water supply indicator as it is the melting snowpack that recharges rivers and the general supply of water

There are other important terms in the hydrologic cycle. The combination of transpiration and evaporation is known as **evapotranspiration**. This is the combination of evaporation and transpiration from plant life to the atmosphere.

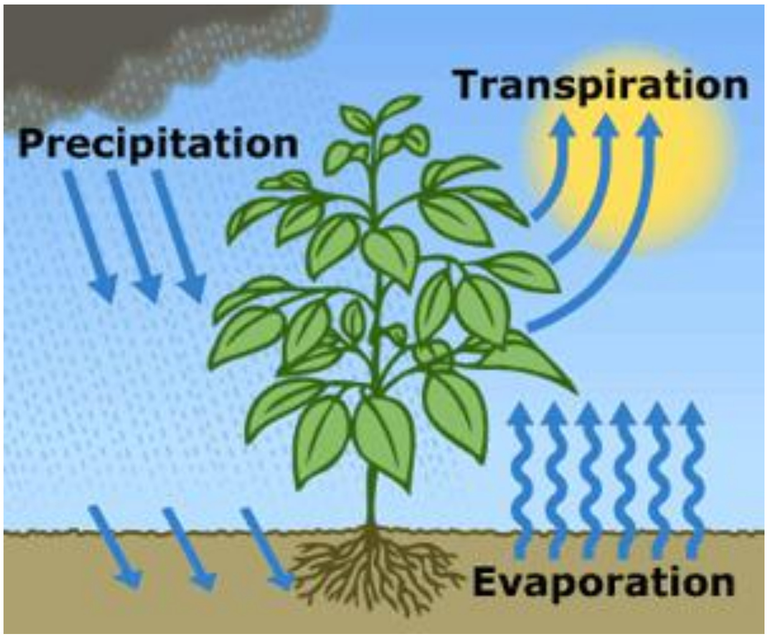


Figure 1.2: Evapotranspiration is the sum of evaporation from the land surface plus transpiration from plants. Precipitation is the source of all water.[2]

GROUNDWATER

Groundwater is one of the two main sources of storage used by municipalities to produce potable water. Groundwater is formed by the percolation of water from the surface of the earth to the subsurface where it is stored in an **aquifer**, a geologic formation that accumulates water in the spaces between the sediment.

[2] Image by the USGS is in the public domain.

Pin It! Misconception Alert
Often aquifers are described as “swimming pools.” This is not a good description. Aquifers store groundwater in the spaces between sediment.

Important characteristics of groundwater include consistent water quality and the ability to remain safe from surface contamination. With greater technology and testing methods chemicals and constituents known to be harmful to humans have been found in numerous well sites throughout the United States. New regulations are continually being updated to ensure source groundwater is safe to drink. In normal circumstances, very little treatment is required to yield groundwater.

The table below describes the benefits and drawbacks of groundwater as a supply source.

Table 1.1 – Benefits and Drawbacks of Groundwater as Supply Source

Groundwater Benefits	Groundwater Drawbacks
• Difficult to pollute • Useful in times of drought when surface supplies are low • Generally, cheaper • No need for an expensive network of pipes and canals to transport long distances	• Difficult to clean up • Replenishment is slow • Hard to manage as levels dwindle • Visual inspection is difficult

The **Groundwater Treatment Rule (GWTR)** was enacted in 2006 to prevent microbial contamination from underground water supplies. The purpose of the new rule was to classify water systems that were at a greater risk for fecal contamination. These systems must employ a multiple barrier protection similar to the surface water treatment rule which will be covered in more detail in the next section.

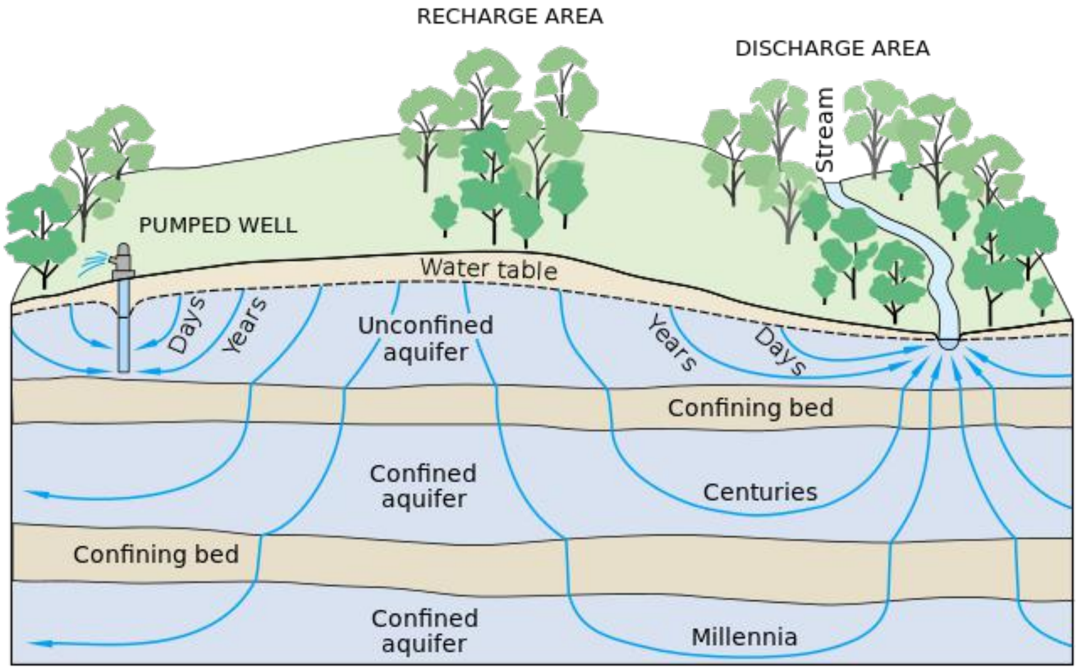


Figure 1.3: Confined & Unconfined Aquifers[3]

There are two kinds of aquifers: confined and unconfined. In an **unconfined aquifer,** the water table is free to rise and fall depending on the amount of precipitation which recharges the aquifer. **Confined aquifers**, contain water that is confined due to layers of low permeability. These layers, which restrict movement, are comprised of rock or hard clay, and are referred to as confining beds, aquitards, or aquicludes. Artesian wells are generally under pressure when drilled. Once drilled the water level at which the column of water will rise is known as the piezometric surface. Sometimes the water will rise to the surface or past the surface but in the instance the water remains below it is known as a non-flowing artesian well.

WELLS

The construction of wells is critical in the extraction of water from underground water supplies. Placement of wells is important because proper location will produce the greatest yield. Important terms related to underground wells are below:

1. **static water level** - the level in the well when no water is being removed from the aquifer. This level can be measured in feet or elevation.
2. **pumping water level** - The level when water is being removed from the aquifer. This level can vary depending on the rate of flow from the well.
3. **drawdown** - The difference between the pumping water level and the static water level
4. **cone of depression** - The shape or “cone” created by the movement of water in all directions during pumping.
5. **well yield** - the amount of water drawn from an aquifer over a specific period

[3] Image by the USGS is in the public domain.

6. **specific capacity** - The amount of water produced per drawdown expressed in gpm/ft
7. **safe yield** - The amount of water that can be pulled from an aquifer per year without a drop in the water table

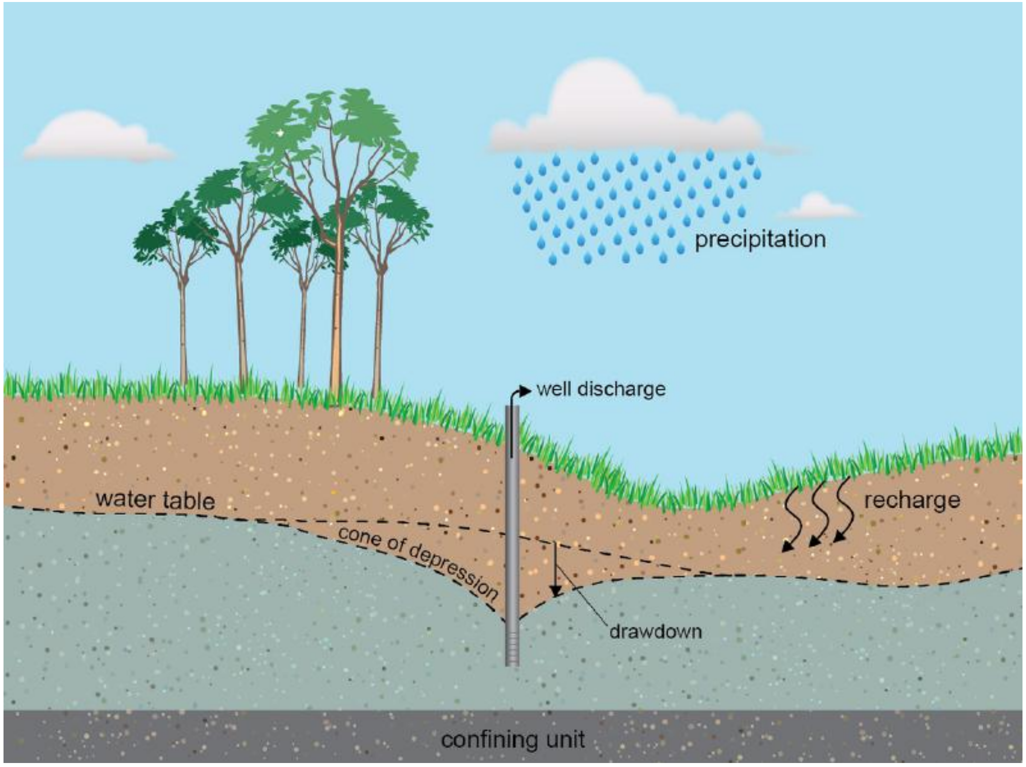


Figure 1.4: Cone of Depression[4]

Specific Capacity Calculation

$$\text{Specific Capacity} = \frac{\text{Flow (gpm)}}{\text{Drawdown (ft)}}$$

Example: A well has a yield of 600 gpm and the drawdown is 50 feet. What is the specific capacity of the well?

$$\text{Specific Capacity} = \frac{600 \text{ gpm}}{50 \text{ ft}} = 12 \text{ gpm/ft}$$

SURFACE WATER

Throughout the United States, surface water is the most widely used source of water for large cities and other municipalities. Surface water includes lakes, ponds, rivers, and streams.

---

[4] Image by USGS is in the public domain.

California is unique as the southern half of the state has 2/3 of the population but only 1/3 of the available water and the northern half of the state has 1/3 of the population but 2/3 of the water. Snowpack in northern California is critical to the state's water supply. Most of Southern California is very arid and densely populated so water travels from Northern California through the State Water Project to Southern California.

Surface runoff supplies water for all surface water sources. Influences of surface runoff include intensity of rainfall, duration of rainfall, composition of soil, amount of moisture in soil, slope of the ground, vegetation coverage, and human influences. If the rainfall density is too great, more water can be lost because the ground will no longer absorb the water. The same applies to the duration of rainfall. Vegetation slows the speed of runoff and allows more water to absorb or infiltrate into the ground. Human influences have a great impact on water runoff. Impervious surfaces like concrete entirely prevent infiltration.

In the table, you can see the benefits and drawbacks of surface water as a supply source.

Table 1.2 – Benefits and Drawbacks of Surface Water as Supply Source

Benefits of Surface Water	Drawbacks of Surface Water
• Easy to access • Lakes and reservoirs can provide flood control in addition to a water supply.	• Water is lost to evaporation. • Lakes and reservoirs may experience a build-up of sediment, especially after fires. • Distribution requires a network of pipes and/or canals.

NATURAL WATERCOURSES

Natural watercourse, including rivers, creeks, streams, and arroyos, flow in one of three ways:

- **perennial streams** - Watercourses which flow continuously throughout the year (e.g., Colorado River)
- **ephemeral streams** - Watercourses that flow sporadically, generally after rainfall. (e.g., Santa Clara River which runs through Santa Clarita and Ventura County)
- **intermittent** streams - Watercourses which flow more often than ephemeral streams, but less often than perennial streams. Rainfall and high groundwater levels will affect how often these streams flow.

Rivers and streams are a good water supply source but may not be reliable.

Figure 1.5: The Colorado River[5]

Figure 1.6: A Map of the Santa Clara River[6]

---

[5] Image of the Colorado River by Paul Hermans is licensed under CC BY-SA 3.0
[6] Santa Clara River Map by Shannon1 is in the public domain.

LAKES

Lakes are the most widely used public water supply source. However, very few “natural” lakes exist. Most lakes used for public water supply are man-made and use a dam to create the lake and contain the water. Water from these lakes is piped to treatment facilities. Due to variances in temperature lakes develop “layers” also known as stratification. Denser, colder water will drop to the bottom (Benthic zone) of a lake during the summer. There are three layers:

- **epilimnion** - The strata closest to the surface of a lake
- **hypolimnion** - The strata near the bottom of a lake
- **thermocline** - middle strata with greatest variance in temperature in a lake

Lake turnover will occur during seasonal temperature changes. When the temperature of a lake is uniform it is known as isothermal. Algae growth is a serious problem that causes taste and odor issues in treated water. Copper sulfate can be added to a lake to help remedy algae blooms. In severe cases the water undergoes eutrophication, which is the loss of oxygen. Complete or extreme oxygen depletion can kill all living creatures in the water including animals and fish.

Figure 1.7 Castaic Lake[7]

[7] Image of Castaic Lake by Rehman is in the public domain.

Key Terms

- **aquifer** – a geologic formation that accumulates water in the spaces between the sediment
- **condensation** – the process in which water moves from a gas to a liquid state
- **cone of depression** – the shape or "cone" created by the movement of water in all directions during pumping
- **confined aquifer** – an aquifer that is limited by layers of low permeability
- **drawdown** – the difference between the pumping water level and the static water level
- **evapotranspiration** – the combination of transpiration and evapotranspiration
- **groundwater** – one of the two main sources of storage used by municipalities to produce potable water
- **Groundwater Treatment Rule (GWTR)** – enacted in 2006 to prevent microbial contamination from underground water supplies
- **ephemeral streams** – watercourses that flow sporadically, generally after rainfall
- **epilimnion** – the layer closest to the surface of a lake
- **hydrologic cycle** – the continual movement of water on the surface of the earth
- **hypolimnion** – the layer near the bottom of the lake
- **infiltration** – the process in which liquid water soaks into the ground; also known as percolation
- **intermittent streams** – watercourses which flow somewhere between ephemeral and perennial streams
- **perennial streams** – watercourses which flow continuously throughout the year
- **precipitation** – the process in which water falls from the sky as rain, snow, sleet, or hail
- **pumping water level** – the level when water is being removed from the aquifer
- **runoff** – the process in which water in the liquid form travels to bodies of water.
- **safe yield** – the amount of water that can be pulled from an aquifer per year without a drop in the water table
- **snowmelt** – the process through which solid water converts to liquid water
- **specific capacity** – the amount of water produced per drawdown expressed in gpm/ft
- **static water level** – the level in the well when no water is being removed from the aquifer
- **subsurface flow** – the process in which water in the liquid state flows below the Earth's surface
- **unconfined aquifer** – an aquifer in which water can move freely
- **thermocline** – middle layer with greatest variance in temperature in a lake
- **transpiration** – the process in which water moves from a liquid to a gas state from plants
- **water storage** – natural storage in liquid form in lakes, ponds, wetlands, and groundwater aquifers
- **well yield** – the amount of water drawn from an aquifer over a specific period

CHAPTER REVIEW

1. What is the middle layer of a stratified lake called?
    a. thermocline
    b. benthic zone
    c. epilimnion
    d. hypolimnion

2. What is the conversion of liquid water to gaseous water?
    a. advection
    b. condensation
    c. precipitation
    d. evaporation

3. How much does water weigh?
    a. 7.48 lbs/gal
    b. 8.34 lbs/gal
    c. 62.4 lbs/ft^3
    d. Both B. and C.

4. What is the static level of an unconfined aquifer?
    a. drawdown
    b. water table
    c. pumping water level
    d. aquitard

5. What is the cause of taste and odor problems in raw surface water?
    a. copper sulfate
    b. blue-green algae
    c. oxygen
    d. lake turnover

6. What chemical reduces blue-green algae growth?
    a. chlorine
    b. caustic soda
    c. copper sulfate
    d. alum

7. What is a water-bearing geologic formation that accumulates water due to its porousness?
    a. aquifer
    b. lake
    c. aquiclude
    d. well

8. What kind of stream flows continuously throughout the year?
    a. ephemeral
    b. perennial
    c. intermittent
    d. stratified

9. What is an aquifer that is underneath a layer of low permeability?
    a. confined aquifer
    b. water table aquifer
    c. unconfined aquifer
    d. unreachable groundwater

10. What is the bottom layer of a stratified lake?
    a. hypolimnion
    b. benthic zone
    c. thermocline
    d. epilimnion

11. What is the amount of water that can be pulled from an aquifer without depleting it?
    a. drawdown
    b. safe yield
    c. overdraft
    d. subsidence

Math Questions

Please show all work. On the State exams you will not get credit if work is not shown.

1. What is the area of the top of a storage tank that is 75 feet in diameter?
    a. 4,000 ft^2
    b. 4416 ft^2
    c. 1104 ft^2
    d. 17,663 ft^2

2. What is the area of a wall 175 ft in length and 20 ft wide?
    a. 3,000 ft^2
    b. 2,500 ft^2
    c. 3,500 ft^2
    d. 4,000 ft^2

3. You are tasked with filling an area with rock near some of your equipment. 1 Bag of rock covers 250 square feet. The area that needs rock cover is 400 feet in length and 30 feet wide. How many bags do you need to purchase?
    a. 40 bags
    b. 42 bags
    c. 45 bags
    d. 48 bags

CHAPTER 2 – WATER CHEMISTRY AND STANDARDS

In this chapter, you will learn about the basic scientific principles related to the water treatment. We will also discuss drinking water standards in the United States and different community standards. After reading the chapter, you should be able to:

- describe elements and compounds;
- differentiate between public water systems;
- differentiate between primary and secondary standards;
- identify common water treatment violations; and
- solve volume problems

ELEMENTS AND COMPOUNDS

Much of what we treat in drinking water treatment cannot be seen. For this reason, it's important to understand how atoms, elements and compounds are related and important even though we cannot see them directly. The smallest parts of an element are comprised of particles known as **atoms**. Even though they are so small, atoms still retain the characteristics of the element. Even with technological advancements, microscopes are still unable to capture atoms. The multiple arrangements of atoms make each element unique. The atom ever so small, is comprised of three particles known as the proton, neutron, and electron. Each particle is associated by different charges.

- Proton - positive
- Neutron - no charge
- Electron - negative charge

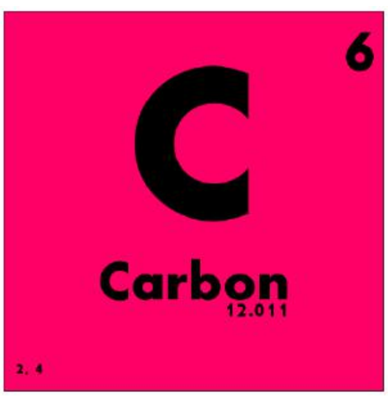


Figure 2.1: Carbon[8]

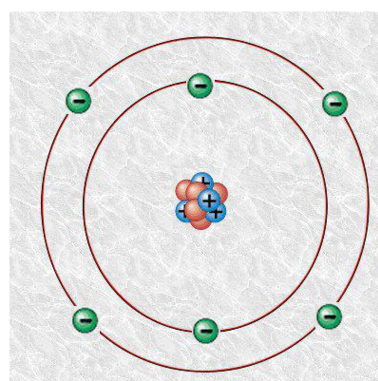


Figure 2.2: Carbon Atom[9]

[8] Carbon by Science Activism is licensed under CC BY 2.0
[9] Carbon atom by Alejandro Porto is licensed under CC BY-SA 3.0

The defining characteristic of an atom is identified by the proton. The proton, located in the nucleus, has a distinctive number. For example, carbon has six protons located in the nucleus. No other element has six protons in the nucleus. The number of protons that exist for a given element is always the same, but the number of neutrons can vary. When there is a varying number of neutrons of a given element, it is known as an isotope. When an atom has a difference in electrons, it is called an ion. When the charges of the atom are not balanced, they become unstable. An atom that has more protons than neutrons is called a **cation**. An atom that has more electrons than protons is called an **anion**.

Most common elements in the water treatment profession include these:

- Aluminum (Al)
- Antimony (Sb)
- Arsenic (As)
- Barium (Ba)
- Beryllium (Be)
- Boron (B)
- Bromine (Br)
- Cadmium (Cd)
- Calcium (Ca)
- Carbon (C)
- Chlorine (Cl)
- Chromium (Cr)
- Copper (Cu)
- Fluorine (F)
- Hydrogen (H)
- Iodine (I)
- Iron (I)
- Lead (Pb)
- Magnesium (Mg)
- Manganese (Mn)
- Mercury (Mn)
- Nickel (Ni)
- Nitrogen (N)
- Oxygen (O)
- Phosphorus (P)
- Potassium (K)
- Radium (Ra)
- Selenium (Se)
- Silicon (Si)
- Silver (Ag)
- Sodium (Na)
- Strontium (Sr)
- Sulfur (S)
- Thallium (Tl)

DRINKING WATER STANDARDS

The first drinking water standards created in the United States occurred in 1974 and were called the **Safe Drinking Water Act (SDWA).** The US EPA sets drinking Water Standards that all Water Municipalities must adhere to. Although states develop their own standards, they must meet the minimum requirements set forth by the federal EPA. In California, drinking water standards are much more stringent than the federal requirements and therefore have primacy. As of 2014, the state regulatory group responsible for drinking water is the State Water Resources Control Board. Revisions to the safe drinking water act include approval techniques for treatment plants, specifying criteria for filtration of public water supplies, distinguishing different treatment techniques for surface and ground water, and prohibiting lead products in drinking water systems.

There are two sets of drinking water standards identified as primary standards and secondary standards. **Primary Standards** effect human health and are mandated with Maximum Contaminant Levels (MCL). The MCL is the official safe level at which a human can consume the given contaminant without adverse health effects. **Secondary Standards** do not affect human health and are controlled with Maximum Contaminant Level Goals. (MCLG). When a contaminant is reported, there is no such thing as zero. Levels are set to protect human health but are also set based on the best available technology. As technology improves MCL's may be reexamined. Instrumentation to measure contaminant levels are not always capable of reading to absolute zero. Because of this a Detection level for reporting is required.

PUBLIC WATER SYSTEMS

There are three different categories of public water systems:

1. Community Public Water System: A community public water system has 15 or more service connections and serves at least 25 or more people year round. These would include municipalities, mobile home parks, condos, and apartment buildings.
2. Nontransient, NonCommunity System: A nontransient, NonCommunity public water system owns their own system and serves an average of 25 people for at least six months. Schools, hospitals, and office buildings are included in this category.
3. Transient, NonCommunity System: A transient, NonCommunity public water system owns their own water system and serves an average of 25 people per day. In this category people consume the water for a short period of time. This category includes churches, parks, restaurants, and motels.

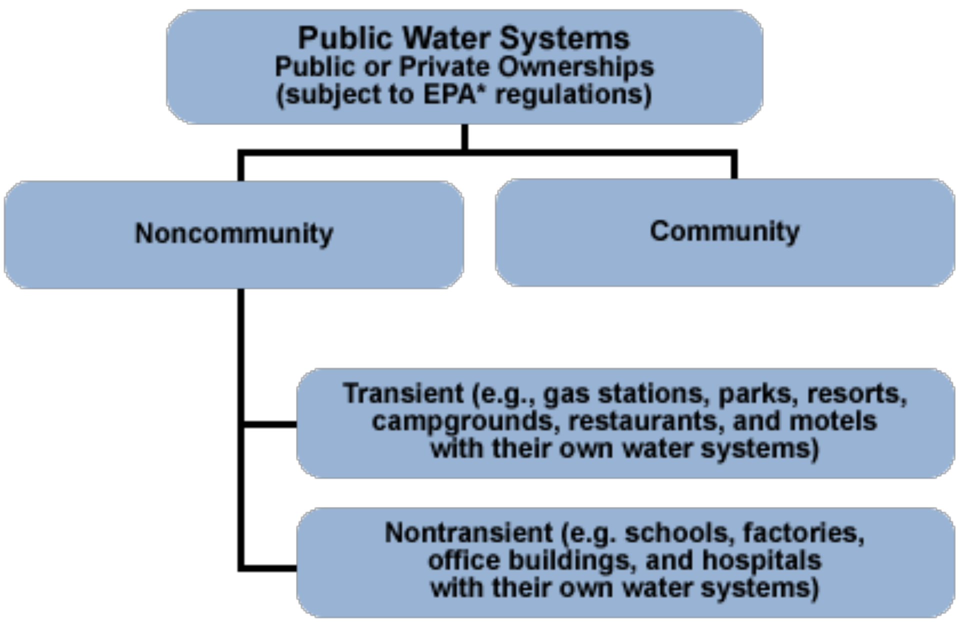


Figure 2.3: Public Water System Chart[10]

Primary Drinking Water Standards are split into five categories. The categories include Inorganics, Organics, Turbidity, Microbiological, and Radiological.

1. Inorganics: metals, nitrate, and fluoride
2. Organics: Pesticides, solvents, and disinfectant by-products (DBPs) - The combination of chlorine and natural organic material. This topic will be discussed in greater detail later in the text.
3. Turbidity: The cloudiness of the water, which can shield microbiological material.

[10] Image by the CDC is in the public domain.

4. Microbiological: coliform testing (This will be covered in greater detail later in the text. Water operators do not test for specific microbiological agents. We test for the indicator organism coliform. They colonize in greater numbers so if a sample comes back positive there is a greater likelihood of fecal contamination.)
5. Radiological: gross alpha, beta, and radon

Secondary drinking water standards are solely based on the aesthetic quality of drinking water. The focus of secondary standards is taste, odor, and color. A glass of water that smells like fish and is orange in color may be "safe" to drink but would not be well received or readily consumed.

Table 2.1 - Recommended Levels for Contaminants and Characteristics[11]

Contaminant/characteristic	Recommended level
Aluminum	0.05 to 0.2 mg/L
Chloride	250 mg/L
Color	15 color units
Copper	1 mg/L
Corrosivity	Non-corrosive
Fluoride	2 mg/L
Foaming agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor number
pH	6.5 to 8.5
Silver	0.10 mg/L
Sulfate	250 mg/L
Total dissolved solids	500 mg/L
Zinc	5 mg/L

PUBLIC NOTIFICATION

If a treatment plant does not meet requirements of the SDWA, the public must be notified. There are three different tiers of notification with Tier I as the worst of violations and Tier III being the least. The EPA provides very specific language for public notifications in the event of a violation. Violating a SDWA compliance is bad enough but failing to report violations brings even stiffer penalties and fines.

In 2014, in Flint, Michigan 15 people were criminally charged due to their negligence in the water treatment profession. It all started when the city of Flint changed their source water without properly testing. Officials knew the water was not safe to drink and numerous

[11] Graph by the EPA is in the public domain.

violations had been made. The public was not properly informed of these violations which resulted in 10 deaths and 77 others becoming severely ill. The most important thing you can do as an operator is say something if there appears to be a problem with the quality of the drinking water, otherwise you may end up in jail. Notification options include radio or television announcements, newspapers, hand delivery, posting in public places, loudspeakers, texting, and reverse 911. The notification will vary based on the severity of the violation.

VIOLATIONS

Tier I

- Any positive fecal coliform positive test and failure to sample after initial positive test.
- Nitrate or nitrite violation
- Chlorine Dioxide Maximum residual disinfection limit
- Exceed treatment plants allowable turbidity level. Can be a tier II if the primacy agency does not elevate violation
- Waterborne emergency or outbreak of waterborne illness

Tier II

- MCL, MRDL and, Treatment Technique (TT) violations if treatment plant does not perform corrective actions to fix issues in treatment plant or fails to inform public.
- Water quality monitoring violation - not taking required water quality samples. Can also be a tier III violation but can be elevated for gross negligence
- Noncompliance of a variance or an exemption

Tier III

- Water testing and monitoring violation
- Any time the treatment system is running under a variance or exception. Primacy agency may give a treatment plant a variance or exemption for a short period of time. The public notification is to inform the public that a water agency is not running in accordance with an approved treatment technique. It does not mean the water is unsafe to drink, but the operating manuals are very specific.

WATER QUALITY MONITORING

Continuous monitoring of drinking water ensures quality; reliable drinking water is being delivered to the public. The number of samples taken, frequency of sampling, sampling location, testing procedures, and requirements for record keeping are all specified by state and federal requirements. If sampling requirements are not met, it can lead to public notification. The tier violation is based on the contaminant and whether the contaminant causes acute health effects.

The type of monitoring is based on the source of the water, the treatment technique, and the size of the system. Reporting and record keeping is based on the primacy agency's regulations. The States regulations must meet federal requirements at a minimum but may be more stringent as is the case in California.

RECORD KEEPING

Below is a list of records that must be kept and the amount of time the records must be retained on file.

- Bacteriological and Turbidity - 5 years
- Chemical analysis - 10 years
- Corrective actions from violations - 3 years
- Sanitary surveys - 10 years
- Exemptions - 5 years after expiration

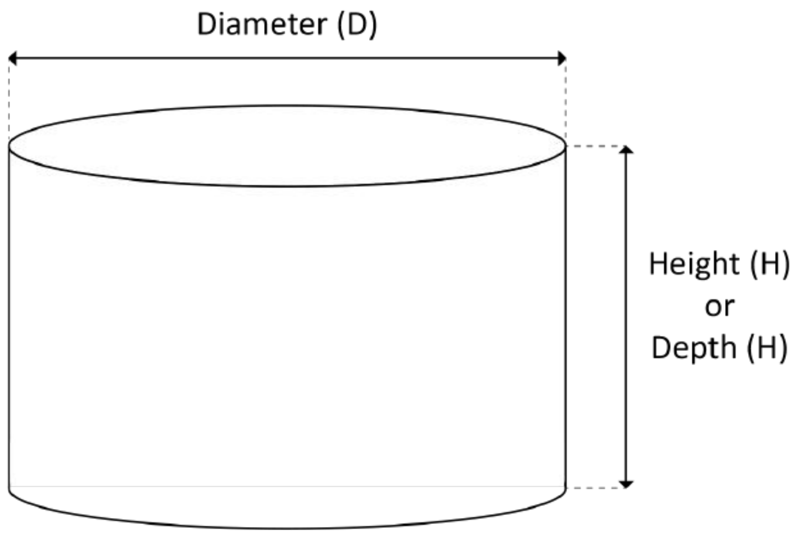
VARIANCES AND EXEMPTIONS

In the event a water system is unable to meet a MCL because of the source water, a primacy agency can grant a variance or exemption. The variance is only given when the agency has incorporated the best available technology and there is zero risk to public health. In the case of Flint, Michigan, the new source water was not properly tested before it was used in the system. Flint Water plant was unable to properly treat the source water, which had elevated levels of lead, and the City was not using the best available technology. Even if the City of Flint would have applied for a variance or exemption, it would not have been granted because the lead levels in the water create a significant risk to public health.

VOLUME

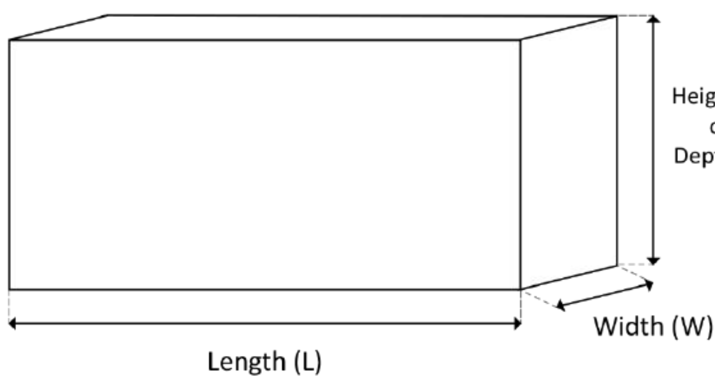
Volume calculations are common for water treatment operators. Operators use volume calculations to solve math questions with circles, triangles, and rectangles. If you look around a water treatment facility, it is full of geometric shapes. Tanks can be cylindrical or rectangular in nature. **Clear wells** that store treated water can have multiple shapes. Settling ponds may have a triangular nature to them.

Cylinder



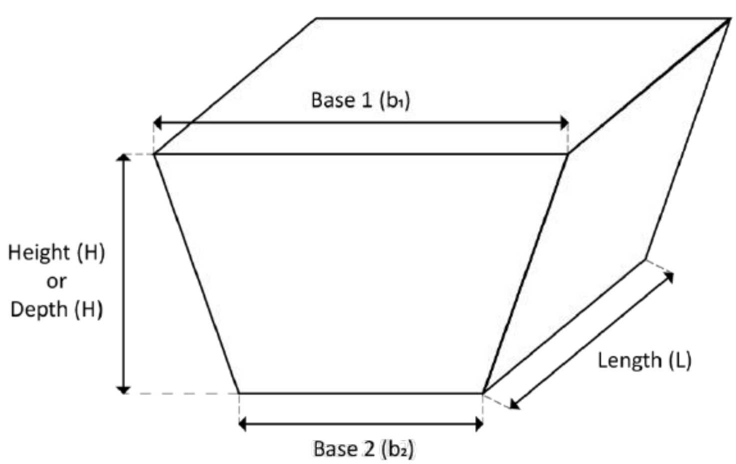
$$\text{Volume} = 0.785 \times D^2 \times H$$

Rectangular Prism



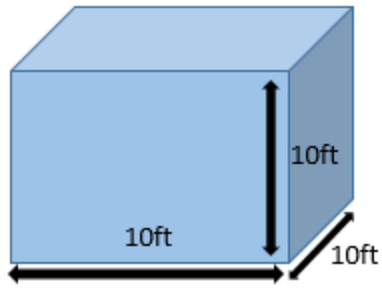
$$\text{Volume} = L \times W \times H$$

Trapezoidal Prism



$$\text{Volume} = \frac{b_1 + b_2}{2} \times H \times L$$

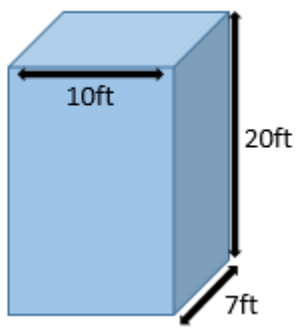
Example: What is the volume of a cubed tank that is 10 feet high? (Remember cubes have the same unit of length on all three sides. This is the easiest problem to solve.)



$$\text{Volume} = L \times W \times H$$

$$\text{Volume} = 10\text{ ft} \times 10\text{ ft} \times 10\text{ ft} = 1{,}000\text{ ft}^3$$

Example: What is the volume of a rectangular tank that is 20 ft high, 10 ft wide, and 7 ft in length?

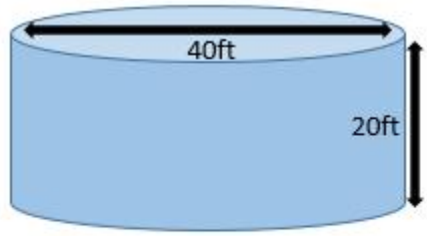


$$\text{Volume} = L \times W \times H$$

$$\text{Volume} = 7\text{ ft} \times 10\text{ ft} \times 20\text{ ft} = 1{,}400\text{ ft}^3$$

There are two different ways to solve cylindrical math problems. The easiest formula to use is volume= .785 d^2 H. This formula is easiest because in water math we are generally looking at the diameter of a cylindrical shape and not the radius. The radius of a circle is half the diameter. It is a straight line measured from the center of the circle to the edge of the circle. The diameter is a straight line that passes through the center of the circle with end points on the circle.

Example: What is the volume of a cylindrical storage tank that measures 40 ft in diameter and is 20 ft deep?



$$\text{Volume} = 0.785 \times D^2 \times H$$

$$\text{Volume} = 0.785 \times (40\ \text{ft})^2 \times 20\ \text{ft}$$

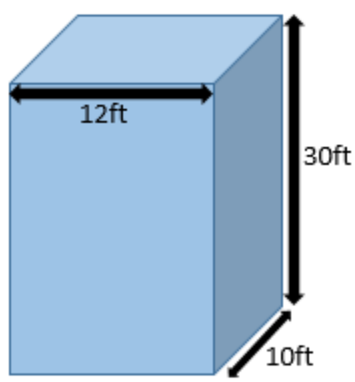
$$\text{Volume} = 0.785 \times 40\ \text{ft} \times 40\ \text{ft} \times 20\ \text{ft} = 25{,}120\ \text{ft}^3$$

Often the water math word problems will require multiple steps to solve. Typically, we want to know how many gallons a given tank will hold. Once we find the volume of the tank in cubic feet, we will then convert the cubic feet into gallons.

Example: Convert the answer from the previous example into gallons.

$$\frac{25{,}120\ \text{ft}^3}{1} \times \frac{7.48\ \text{gal}}{\text{ft}^3} = 187{,}897.6\ \text{gal} = 187{,}898\ \text{gal}$$

Example: A rectangular water tank is full. The dimensions of the tank are 30 ft high 12 ft wide and a length of 10 ft. How many gallons are in the tank?

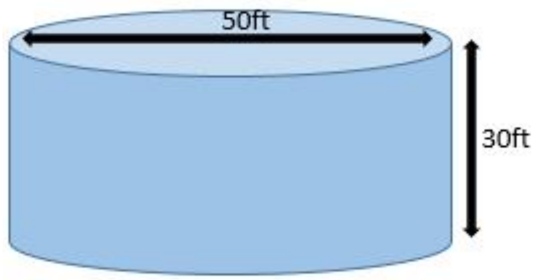


$$\text{Volume} = L \times W \times H$$

$$\text{Volume} = 12\ \text{ft} \times 10\ \text{ft} \times 30\ \text{ft} = 3{,}600\ \text{ft}^3$$

$$\frac{3{,}600 \text{ ft}^3}{1} \times \frac{7.48 \text{ gal}}{\text{ft}^3} = 26{,}928 \text{ gal}$$

Example: A cylindrical storage tank has a diameter of 50 ft and a height of 30 ft. The tank is half full. How many gallons are in the tank?



$$\text{Volume} = 0.785 \times D^2 \times H$$

$$\text{Volume} = 0.785 \times (50 \text{ ft})^2 \times 30 \text{ ft}$$

$$\text{Volume} = 0.785 \times 50 \text{ ft} \times 50 \text{ ft} \times 30 \text{ ft} = 58{,}875 \text{ ft}^3$$

$$\frac{58{,}875 \text{ ft}^3}{1} \times \frac{7.48 \text{ gal}}{\text{ft}^3} = 440{,}385 \text{ gal}$$

This is the total number of gallons the tank can hold when full. Since the problem statement says the tank is half full, divide the total gallons by 2.

$$\frac{440{,}385 \text{ gal}}{1} \times \frac{1}{2} = 220{,}192.5 \text{ gal} = 220{,}193 \text{ gal}$$

Another way to approach this problem is to calculate the gallons based on a height of 15 ft of tank which is the height of the water when the tank is half full.

$$\text{Volume} = 0.785 \times (50 \text{ ft})^2 \times 15 \text{ ft}$$

$$\text{Volume} = 0.785 \times 50 \text{ ft} \times 50 \text{ ft} \times 15 \text{ ft} = 29{,}437.5 \text{ ft}^3$$

$$\frac{29{,}437.5 \text{ ft}^3}{1} \times \frac{7.48 \text{ gal}}{\text{ft}^3} = 220{,}192.5 \text{ gal} = 220{,}193 \text{ gal}$$

Note that the final answer is the same.

Key Terms

- **anion** – an atom that has more electrons than protons
- **atom** – the smallest part of matter that retains the characteristics of an element; contains protons, neutrons, and electrons
- **cation** – an atom with more protons than neutrons
- **clear well** – storage for treated water
- **primary standards** – water standards for contaminants that effect human health; have maximum contaminant levels (MCLs)
- **Safe Drinking Water Act (SDWA)** – signed into law in 1974, the SDWA gives the federal government the authority to set national standards for contaminants in drinking water, require public water systems to monitor and report their contaminants and set uniform guidelines specifying the acceptable treatment technologies for cleaning drinking water of unsafe levels of pollutants
- **secondary standards** – water standards that are for aesthetic characteristics and do not affect human health; have Maximum Contaminant Level Goals (MCLGs)

CHAPTER REVIEW

1. What is the smallest part of an element?
   a. proton
   b. neutron
   c. atom
   d. nucleus

2. What is an atom with a positive charge?
   a. neutrons
   b. protons
   c. electrons
   d. atoms

3. What is an atom with a negative charge?
   a. proton
   b. neutron
   c. nucleus
   d. electron

4. What does the symbol mg/L stand for?
   a. micrograms per liter
   b. milligrams per/L
   c. parts per million
   d. both B & C

5. What does the acronym MCL stand for?
   a. minimum contaminant level
   b. micron contaminant level
   c. maximum contaminant Level
   d. milligrams counted last

6. How long do sanitary surveys have to be retained for records?
   a. 3 years
   b. 5 years
   c. 7 years
   d. 10 years

7. What is the most severe water system violation that requires the fastest public notification?
   a. Tier I
   b. Tier II
   c. Tier III
   d. Tier IV

8. When can the primary regulating agency grant a variance or exemption?
    a. The agency is using the Best Available Technology.
    b. There is no threat to public health.
    c. There is never a scenario for a variance or exemption.
    d. Both A. and B.

9. What is a public water system that serves at least 25 people six months out of the year?
    a. nontransient noncommunity
    b. transient noncommunity
    c. community public water system
    d. None of the above.

10. What are regulations based on the aesthetic quality of drinking water?
    a. primary standards
    b. secondary standards
    c. microbiological standards
    d. radiological standards

11. What is the lowest reportable limit for a water sample?
    a. 0.5 mg/L
    b. Zero
    c. public health goal
    d. detection Level for reporting

12. What is the basis for Primary Standards?
    a. color and Taste
    b. aesthetic quality
    c. public Health
    d. odor

13. A circular clear well is 150 feet in diameter and 40 feet tall. The clear well has an overflow at 35 feet. What is the maximum amount of water the clear well can hold in million gallons rounded to the nearest hundredth?
    a. MG
    b. 4.62 MG
    c. 18.50 MG
    d. 7.50 MG

14. A sedimentation basin is 400 feet length, 50 feet in width, and 15 feet deep. What is the volume expressed in cubic feet?
    a. 100,000 ft^3
    b. 200,000 ft^3
    c. 300,000 ft^3
    d. 400,000 ft^3

15. A clear well holds 314,000 ft^3 of water. It is 100 ft in diameter. What is the height of the clear well?
    a. 25 ft
    b. 30 ft
    c. 35 ft
    d. 40 ft

CHAPTER 3 – MICROORGANISMS

The most important job of a water treatment operator is providing reliable and quality water to the public. This is accomplished through chemical deactivation or physical removal of disease-causing microorganisms in the water. Microorganisms are deactivated by the addition of a chemical such as chlorine or ozone while physical removal is accomplished with the use of a filtration system. After reading the chapter, you should be able to:

- identify common waterborne pathogens;
- describe water quality rules and parts of the Consumer Confidence Report; and
- solve math problems involving volume.

SURFACE WATER TREATMENT RULE

The Surface Water Treatment Rule (SWTR) was created in 1990 to further protect the public from waterborne illness. The specific diseases the SWTR seeks to prevent are those caused by viruses, legionella, and *Giardia* lamblia. Disease-causing microorganisms are also known as **pathogens**. The microbes that cause most waterborne illnesses are found in most surface water in the United States. Every public agency that uses surface water as source water must adhere to the SWTR. Surface Water is defined as any open body of water that is susceptible to surface runoff. Rainfall and snowmelt that enters open bodies of water such as lakes, rivers, and man-made reservoirs is susceptible to contamination from sewage treatment plants and animal feces.

At this time, there are no simple inexpensive tests for viruses, legionella, and *Giardia* lamblia; therefore, other protective measures are used to test the source water and treated water. Water regulations provide detailed inactivation and removal regulations for Protozoa, also known as *Giardia*, and viruses. Bacteria fall somewhere in the middle of both microorganisms so there is no need to “regulate” them. Bacteria will be removed and/or deactivated within the parameters or regulations that are in place. *Giardia* and *Cryptosporidium* form hard cysts that are very difficult to deactivate chemically with chlorine. They are larger than viruses so they or more easily removed through filtration. Newer technological advances such as ozone addition are excellent ways to deactivate *Giardia*.

Treatment plants must use a combination of disinfectant (chemical deactivation) and filtration and must achieve 99.9% removal or inactivation of *Giardia* cysts and 99.99% of viruses. You might also see the percentages expressed as 3 Log and 4 Log. 99.9% will be expressed as 3 Log and 99.99% will be expressed as 4 Log. Treatment plants which use filtration achieve their removal factor by monitoring the combined filter effluent turbidity. **Turbidity** is the measurement of the cloudiness in water. The reason it is important to measure turbidity is because microorganisms can hide behind the very small particles and render treatment techniques ineffective. Turbidity readings are expressed as nephelometric turbidity units (NTU).

The approved treatment techniques currently used by water operators are conventional treatment, direct filtration, slow sand, diatomaceous earth, reverse osmosis, and alternate treatment technologies approved on a case by case basis by the primacy regulating board. Newer technologies such as membrane filtration and UV treatment are being employed by some water agencies.

Table 3.1 - Waterborne Pathogens

Bacteria	Viruses	Protozoa
• Campylobacter • Escherichia coli (E-coli) • Salmonella • Yersinia • Vibrio • Legionella • Aeromonas • Mycobacterium • Shigella • Pseudomonas	• Hepatitis A • Reovirus • Calicivirus • Enterovirus • Coxsackievirus • Adenovirus • Echovirus • Poliovirus	• *Giardia Lamblia* • *Cryptosporidium* • Entamoeba • Microsporidium

A continuous disinfectant residual must always be in the distribution system to prevent waterborne illness. A disinfectant residual of .2 mg/L must always be present in the distribution system, however most water operators will maintain somewhere between 2.5 mg/L-3.0 mg/L. The CT calculation is used to make sure proper disinfectant levels are being used during the treatment and distribution process. The effectiveness of the treatment process is calculated with the CT formula and uses data such as disinfectant used, residual of disinfectant, length of time disinfectant is in contact with water, water temperature, and pH of the water. It is important to note that during the treatment process the goal is to disinfect the water (kill all pathogens) and not to sterilize (kill all organisms).

The “C” is the concentration of disinfectant while the “T” is the amount of time the disinfectant is in contact with water. On days with higher effluent plant rates, an operator may need to raise chlorine doses as the disinfectant will be in contact with the water for less time. Conversely, if plant flow rates are lower, a lower chlorine dose can be used because the disinfectant is in contact with the water for a greater time.

Case Study: Milwaukee April 1993

In April of 1993, the largest outbreak of *Cryptosporidium* on record occurred in Milwaukee, Wisconsin. Over 400,000 people reported illness and 100 people died. Most of the people who died were HIV positive. It cannot be for certain that the *Cryptosporidium* was the cause of each of their deaths, but as will be discussed later in this chapter, people with weakened immune systems are much more susceptible to death if they drink tainted water.

The Milwaukee incident was the catalyst for enhancements to the SWTR. Since *Cryptosporidium* creates cysts and is not killed by chlorine, the “double barrier” treatment approach was created. Treatment plants were then required to monitor turbidity effluent levels and use alternative treatment techniques, such as ozone or ultraviolet light, that would deactivate the *Cryptosporidium*. An effective filtration plant using coagulation, flocculation, sedimentation, and filtration, should have been able to handle the outbreak, thus turbidity levels were not within standards.

The source of the *Cryptosporidium* was believed to be a sewage spill that was very close to the intake of the Southern Milwaukee treatment plant where the outbreak occurred. Others believe that the operators of the treatment plant were using higher quantities of waste stream water in the treatment process. Recycling washed filter water is a common practice, but after this event it was established that only 10% of the sourced raw water can come from the wastewater.

The lessons everybody learned here is water quality is ever-changing and evolving. Mother Nature throws curveballs at us that change the quality of the source water. If something is wrong, it is your duty as an operator to say something. Regulations are all well and good but if they are not being followed, people can become very ill or possibly even die.

TOTAL COLIFORM RULE

The **Total Coliform Rule** was published in 1989 and was revised in 2014. It set up minimum requirements for the frequency and number of coliform tests that would be taken by water agencies. As discussed earlier, the coliform bacteria exist in larger quantities than other bacteria. If there is a positive coliform test, there is a greater chance the treatment process is not functioning properly and there is an increased chance of pathogens in the water. Bacterial outbreaks in water cause gastroenteritis with the associated symptoms of nausea, diarrhea, vomiting, and cramps. Very young people, elderly, and people with weakened immune systems are at an even greater danger should there be waterborne illnesses in water. Each water agency is required to have an approved sampling site map approved by the primacy agency.

The Total Coliform Rule goal is zero positive coliform samples. Water systems that take less than 40 samples per month are only allowed one positive sample while systems which take greater than 40 samples must not find positive results in more than 5% of the coliform samples taken. If a positive coliform sample is found, it is not necessarily an indicator of a problem. Human sampling error could be the culprit. Once a positive is found the coliform sample is retaken within 24 hours at the positive sampling site and two additional samples are taken, one upstream and one downstream of the initial positive site. If there is a second positive coliform result, the water is then tested for E-Coli. If E-Coli is present in the sample, it is an immediate public health risk and is deemed an acute MCL violation. This would be considered a Tier I violation and public notification would have to occur within 24 hours.

LONG-TERM 1 ENHANCED SURFACE WATER TREATMENT RULE

The Long-Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) applies to water systems which serve less than 10,000 people. Below is a list of requirements for water agencies which fall under this category.

- Must achieve 99% or 2 log removal of *Cryptosporidium.*
- Most systems are required to meet turbidity standards of 0.5 NTU from 95% of combined filter effluent turbidity readings. Smaller systems will get 2 log removal credit of *Giardia* with a stricter .03 NTU combined filter effluent.
- Monitoring of individual filter is required. Higher turbidity reading from individual filters will require corrective action.
- Some states might require a disinfectant by-product profile.
- Any change in primary disinfectant must be profiled and approved.
- All treated water clear wells must be covered and not open to atmosphere.

LONG-TERM 2 ENHANCED SURFACE WATER TREATMENT RULE

The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) covers all water systems which serve more than 10,000 customers.

- This rule added enhancements to the SWTR. Water providers are required to test the source raw water for *Cryptosporidium* and E-coli for a 2 year period. This step was put in to ensure all treatment plant equipment was capable of properly deactivating and removing pathogens from water.
- After testing, systems were given a bin number which determined how susceptible the system was to contamination.
- If systems were susceptible, a time frame was given to correct deficiencies.
- Continuous monitoring of the distribution system influent and maintaining at least .02 mg/L chlorine residual is required.

FILTER BACK WASH RECYCLING RULE

As noted in the Milwaukee case study, water systems can use recycled wastewater as a raw water source. Many treatment plants utilize waste ponds, waste lagoons, and waste basins to capture recycled wash water and water from drains throughout treatment plant. For plants to use the recycled water, plants must put the wastewater through the same treatment process as raw untreated water. The amount of water that can be returned is based on the plants size and maximum plant flows.

LEAD AND COPPER RULE

The lead and copper rule differs from most other water guidelines because these two constituents are usually found in water after it has gone through the treatment cycle. Most untreated or raw water has very low levels of lead and copper. Lead and copper are found in drinking water after a chemical reaction takes place in distribution pipes. Water that is more acidic can erode lead and copper pipes causing them to leach into water. The use of lead pipes in drinking water systems was banned in 1986 and they can no longer be used. Lead is known to cause several health problems in fetuses and young children. It can cause developmental problems. Lead can also have effects on the kidney, brain, red blood cells, and is known to cause anemia.

With optimal corrosion control, the ability of water to chemically react with lead and copper pipes is lowered. Many treatment plants add chemicals such as caustic soda to raise the pH of the water. Treated water with a pH around 8 will keep a thin layer of calcium on the inside of a distribution pipe which protects the pipe from corrosion. Corrosion control is tested by monitoring the conductivity, testing pH of water, water temperature, testing for calcium, testing for alkalinity, and testing for phosphate or silica corrosion inhibiter if used to control corrosion.

The Lead and Copper rule also differs from other rules because it bases its parameters on action levels. If 10 percent of the customers' water tests in the 90^{th} percentile of the action level for lead and copper, then further preventative actions must be met. Most customers do not have to worry about this due to advances in corrosion control in the past few decades.

STAGE 1 AND 2 DISINFECTANT BY-PRODUCT RULE

When natural organic matter mixes with chemical disinfectants, it is possible for disinfectant by-product formation (DBP). Chemical disinfectants used in water treatment that form DBPs are chlorine, chlorine dioxide, chloramines, and ozone. The Stage 1 disinfectant by-product rule established MCL's for trihalomethane (TTHM), Haloacetic acid (HAA5), chlorite, and bromate. Compliance is set up on a running annual average for TTHM, HAA5, and Bromate and on a monthly average for chlorite. The rule also set up maximum disinfection levels for chlorine, chloramines, and chlorine dioxide.

The Stage 2 disinfectant by-product rule applies to all community and nontransient noncommunity water systems that add a chemical disinfectant or purchase treated water that has a chemical disinfectant. The purpose of the Stage 2 rule is to monitor local sampling of individual connections. Some parts of the water system have less movement; therefore, they are more susceptible to DBP formation. The Stage 2 rule covers TTHM and HAA5 and has the same MCL as the Stage 1 rule. See Table 3.2:

Table 3.2

Disinfectant Residual	MRDL* as mg/L	Compliance Based On
Chlorine	4.0 mg/L	Running annual average RAA
Chloramines	4.0 mg/L	Running annual average RAA
Chlorine Dioxide	0.8 mg/L	Daily samples

*Maximum residual disinfectant level

Disinfection By-product	Maximum Contaminant Level	Compliance Based On
Trihalomethane	.080 mg/L (80 ppb)	Running annual average
Haloacetic acid	.060 mg/L (60 ppb)	Running annual average
Bromate	.010 mg/L (10 ppb)	Running annual average
Chlorite	1.0 mg/L (1 ppm)	Monthly average

*ppb- parts per billion ppm- parts per million

CONSUMER CONFIDENCE REPORTS

The public has a right to know what is in their drinking water. As you continue to read through the text you will notice that a lot of the terminology is quite a mouthful. In 1998 consumer confidence reports were made available to the public for transparency. Eight groups of information were added to the report:

- System information including contact info
- Different sources of water (i.e. lakes, wells, rivers)
- Definitions non water personnel can understand including MCL's, MCLG's and treatment techniques
- Any detected contaminants in system along with a listing of the possible health effects if limits and goals are not met
- Non-regulated contaminants found
- List of violations if they occurred
- Variances and exemptions
- Educational tools for contaminants and effected populations

The internet has made it possible for water treatment facilities to post information monthly on company websites; however, a consumer confidence report must be made available on a yearly basis. See Appendix A for examples of methods of communicating this important information.

FLOW RATE CALCULATIONS

The flow rate calculation will be one of the most frequently used in water math. This calculation tells us a lot about what is going on in our water system. Common flow rates you will see are

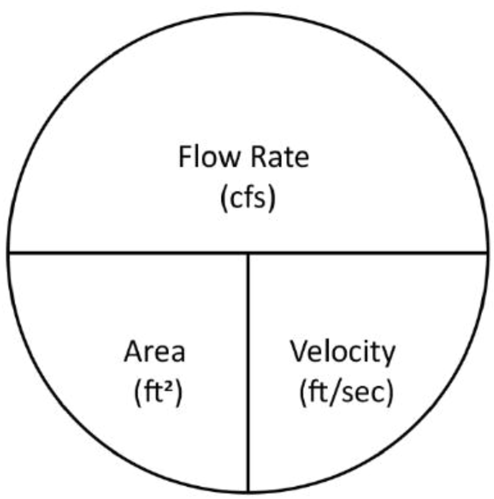
Gallons per Minute (GPM), Cubic Feet Per Second (CFS), Million Gallons a Day (MGD), and Acre Feet per Year (AFY). Water operators use flow rates for different purposes. If you were running a small treatment plant, you might use GPM or CFS in your day to day operations but when looking at water produced throughout the entire month or year, calculating in acre-feet may be more appropriate. Like any algebraic formula there will be an unknown factor you are solving for. In the case of a flow question, there will be 3 values, two known and one unknown.

$$\text{Flow Rate} = \frac{\text{Volume}}{\text{Time}}$$

Flow Rate may also be expressed as:

$$\text{Flow Rate (cfs)} = \text{Area (ft}^2) \times \text{Velocity (ft/sec)} \rightarrow Q = A \times V$$

You may choose to use the "Pie Wheel" to calculate Flow Rate. The Pie Wheel is a visual tool for solving an equation. Anything in the bottom half of the pie wheel is multiplied together to get the answer in the top half of the circle. Thus, using the flow rate formula, Area times Velocity equals Flow Rate. If the top half of the circle, Flow Rate, is given and the question is asking for either Area or Velocity, then you divide the top half of the circle, Flow Rate, by the bottom half, either Area or Velocity, to get the missing value.



Example: In 4 hours, a water tank's volume increases by 30,000 gallons. What was the flow rate of the water entering the tank? Express your answer in gallons per minute.

$$\text{Flow Rate} = \frac{\text{Volume}}{\text{Time}}$$

$$\text{Flow Rate} = \frac{30{,}000 \text{ gal}}{4 \text{ hrs}} \times \frac{1 \text{ hr}}{60 \text{ min}} = \frac{30{,}000 \text{ gal}}{240 \text{ min}} = 125 \text{ gpm}$$

We can also use the Flow Rate equation to solve for volume or time.

Example: How long will it take to drain a 100,000 gallon storage tank where the water is exiting at 2,500 Gallons per minute?

$$\text{Flow Rate} = \frac{\text{Volume}}{\text{Time}}$$

$$\text{Time} = \frac{\text{Volume}}{\text{Flow Rate}}$$

$$\text{Time} = \frac{100{,}000 \text{ gal}}{2{,}500 \text{ gpm}} = 40 \text{ minutes}$$

Example: Your water tank pump is set to run for 90 minutes. Your pump output is 3,000 GPM. How many gallons of water will enter the tank?

$$\text{Flow Rate} = \frac{\text{Volume}}{\text{Time}}$$

$$\text{Volume} = \text{Flow Rate} \times \text{Time}$$

$$\text{Volume} = \frac{3{,}000 \text{ gal}}{\text{min}} \times 90 \text{ min} = 270{,}000 \text{ gal}$$

Example: A water tank's full capacity is 500,000 gallons. The operator will bring the tank down to half full in an 8-hour period. What is flow rate of the water exiting the tank?

$$\text{Flow Rate} = \frac{\text{Volume}}{\text{Time}}$$

$$\text{Flow Rate} = \frac{250{,}000 \text{ gal}}{8 \text{ hrs}} \times \frac{1 \text{ hr}}{60 \text{ min}} = 520.8333 \text{ gpm} = 520.8 \text{ gpm}$$

Note: The state gets very creative with their test questions. Remember to read the question multiple times before solving. Do not be the test taker that uses 500,000 gallons in the equation instead of 250,000 gallons!

Key Terms

- **pathogens** – disease-causing organisms
- **turbidity** – measurement of cloudiness of the water

CHAPTER REVIEW

1. What is a disease-causing microorganism?
    a. pathogen
    b. colilert
    c. pathological
    d. turbidity

2. According to Surface Water Treatment Rule, what is the combined inactivation and removal for *Giardia*?
    a. 1.0 Logs
    b. 2.0 Logs
    c. 3.0 Logs
    d. 4.0 Logs

3. What is the equivalency expressed as a percentage for the SWTR inactivation and removal of viruses?
    a. 99.9%
    b. 99.99%
    c. 99.0 %
    d. 99.999 %

4. A water agency that takes more than 40 coliform samples. What percentile must it fall under?
    a. 10%
    b. 7%
    c. 5%
    d. No positive samples allowable

5. Which does the multiple barrier treatment approach include?
    a. sterilization and filtration
    b. disinfection and filtration
    c. disinfection and sterilization
    d. infection and filtration

6. What is the maximum disinfectant residual allowed for chlorine in a water system?
    a. .02 mg/L
    b. 2.0 mg/L
    c. 3.0 mg/L
    d. 4.0 mg/L

7. How do water agencies monitor the effectiveness of their filtration process?
    a. alkalinity
    b. conductivity
    c. turbidity
    d. pH

8. What is the disinfectant by-product caused by ozonation?
    a. trihalomethanes
    b. bromate
    c. chlorite
    d. no DBP formation

9. What is another term for Haloacetic acids?
    a. TTHM
    b. HOCL
    c. Chlorite
    d. HAA5

10. What is the MCL for trihalomethanes?
    a. .10 mg/L
    b. .06 mg/L
    c. .08 mg/L
    d. .12 mg/L

11. What is the MCL for Haloacetic Acids?
    a. 100 ppb
    b. 60 ppb
    c. 80 ppb
    d. 120 ppb

12. What is the MCL for bromate?
    a. .010 mg/L
    b. .020 mg/L
    c. .030 mg/L
    d. .040 mg/L

13. A treatment plant operator must fill a clear well with 10,000 ft^3 of water in 90 minutes. What is the rate of flow expressed in GPM?
    a. 111 GPM
    b. 831 GPM
    c. 181 GPM
    d. 900 GPM

14. A water tank has a capacity of 6MG. It is currently half full. It will take 6 hours to fill. What is the flow rate of the pump?
    a. 3,333 GPM
    b. 6,333 GPM
    c. 8,333 GPM
    d. 16,666 GPM

15. A clear well with the capacity of 2.5 MG is being filled after a maintenance period. The flow rate is 2,500 GPM. The operator begins filling at 7 AM. At what time will the clear well be full?
    a. 10:00 PM
    b. 10:40 PM
    c. 11:00 PM
    d. 11:40 PM

CHAPTER 4 – COAGULATION AND FLOCCULATION

The physical removal of pathogens is accomplished in several steps. The first two steps include the processes of coagulation and flocculation. In this process colloidal particles are destabilized to gather all the suspended material together. They can also be referred to as nonstable solids. This process increases particle sizes which assists in removal during the filter process. The larger floc particles will be removed during the sedimentation and filtration process. Coagulation occurs very quickly in the rapid mix or flash mix process. **Coagulation** is the physical and chemical reaction occurring between the alkalinity of the water and the coagulant added to the water, which results in the formation of insoluble flocs. The flash mix process only lasts several seconds as the coagulant rapidly mixes and reacts with the raw untreated water. The floc will gain in size during the second step of flocculation. Filtration cannot occur without proper coagulation and flocculation. After reading this chapter, you will be able to:

- differentiate between coagulation and flocculation;
- describe coagulation chemistry; and
- apply the Pounds Formula.

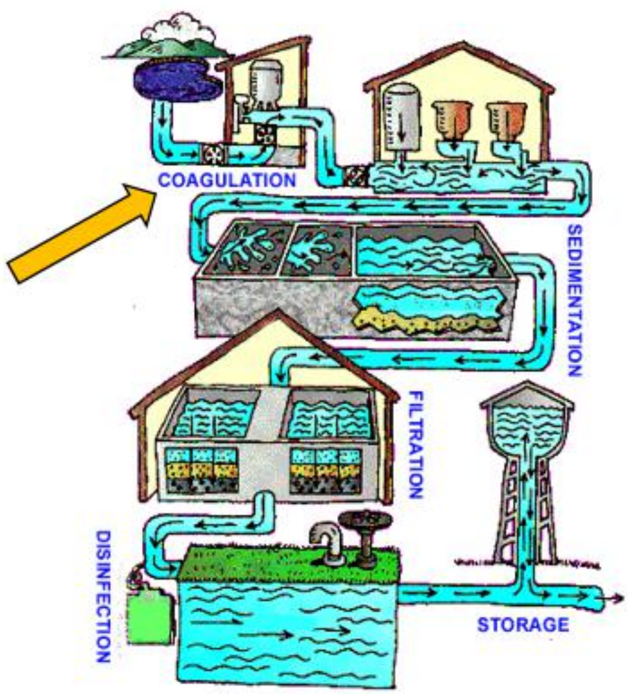


Figure 4.1: The Water Treatment Process[12]

[12] Image of water treatment by the EPA is in the public domain.

COAGULANT TYPES

In general, two types of coagulants are used during coagulation. A primary coagulant and a coagulant aid will be used during the rapid mix process. The colloidal surfaces are negative thus positively charged metal salts are used as primary coagulants. The coagulant dissolves in water and ionizes. To ionize is when a molecule loses or gains an electron to form an ion. The three most common coagulants used in water treatment are Aluminum Sulfate (Alum), Ferric Sulfate, and Ferric Chloride. The most used primary coagulant in water treatment is alum because of its wide availability and affordability.

Synthetic polymers are often used as a coagulant and filter aid but have also been used as a primary coagulant. Operators use different charged groups of polymers known as cationic (positive), anionic (negative), and nonionic (without ionizable groups). Coagulation aids assist in the building of settable floc.

Important things to consider when choosing a polymer:

- Overdosing a polymer can decrease the efficiency of the coagulation process and cause filter binding and increased head loss in filters.
- Not all supply water is created equal. Every single water source has different chemistry and jar tests must be performed to see what polymer works best with the specific source water.
- There is no widespread standard for choosing a polymer. Different states have chemical approval standards that must be met.
- The addition of chlorine can affect polymer effectiveness.
- As with any chemical, there is a dosage limit.

CHEMISTRY

As an operator, you should have a basic understanding of the chemistry involved in each process in water treatment, including coagulation. In coagulation, the coagulant added to the water will react with the alkalinity in the water to form insoluble floc. Insoluble is something that will not dissolve. If the floc is not formed properly, then operators cannot effectively remove pathogens from the treated water. Alkalinity is not the same as pH. This gets very confusing as “alkaline water” has become a more widely popularized marketing term. Alkalinity is the water’s ability to neutralize an acid based on its makeup of carbonate, bicarbonate, or hydroxide. The measure of alkalinity is the amount of acid that would have to be added to water to lower the pH to 4.5 and there is where the confusion arises.

Coagulation is most effective in the pH range of 5-7 because of the waters ability to react with alkalinity. In this range the water tends to buffer or stay in the same pH range and will allow the complete mixing of coagulant chemicals. If the raw water has a low pH, agents such as soda ash can be added to increase the pH.

Proper water quality tests must be performed by operators to promote the proper addition of coagulant chemicals. Under dosing coagulants will cause problems with floc formation while overdosing coagulants can cause clogging during the filter process. Clogged filters lead to head loss problems in the filters and increased filter washing.

MIXING

Mixing can be achieved by utilizing hydraulic mixers, mechanical mixing, diffusers, or pumped blenders. Hydraulic mixers use flow to achieve mixing. This kind of mixing requires enough flow to create a disturbance in the water to achieve proper mixing. Mechanical mixers require the greatest amount of energy because they require an electrical source to achieve mixing. Diffusers apply uniform flow during the coagulation process but may require many adjustments after flow changes. Finally, pumps can be used to push coagulant into water flow. Mixing can occur in a basin, channel, or pipeline.

FLOCCULATION

Flocculation is the slow stirring process that causes the gathering together of small, coagulated particles into larger, settleable particles. The particles are then more easily removed in the sedimentation and filtration process. The process of flocculation is achieved by controlling the rate of impacts between particles as they gain size. Floc size can range between .1 mm-3 mm. The size of the floc produced depends on which type of treatment process is utilized at a specific plant. It is important that floc has good size but also density so the floc will not shear during the sedimentation and filtration process. This process is much longer than coagulation lasting roughly 15-45 minutes.

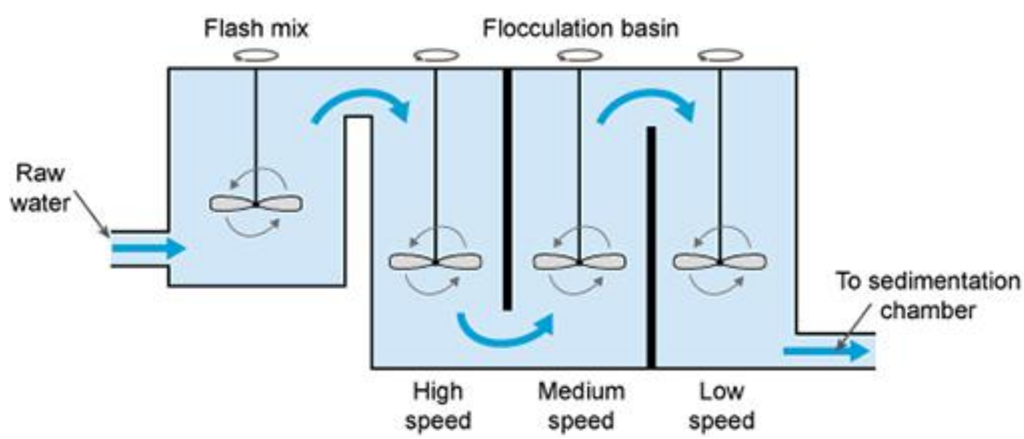


Figure 4.2: The Coagulation-Flocculation Process[13]

The flash mix portion is also known as coagulation. The chemicals are added together, and the process occurs within seconds. After flash mix, the water heads to the flocculation basins to allow floc particles to gather in size.

[13] The coagulation–flocculation process by The Open University and partners is licensed under CC BY-NC-SA 4.0

Mechanical flocculators can be installed both horizontally and vertically. The horizontal type utilizes paddle style mixers while the vertical style mixers can include paddle, turbine, and propeller style mixers. The shape and size of a flocculation basin is determined by the type of mixing used and the adjacent structures such as the sedimentation basins. Flocculation basins are usually split into 3 compartments. The speed of the mixing is decreased in each compartment to prevent the particles from breaking apart as they become larger. If the particles break apart during flocculation, the particles will place a heavier burden on the filters during the filtration process causing lower filter run times. This phenomenon will be discussed in further detail in chapter #6.

MONITORING AND PROCESS CONTROL

The coagulation and flocculation process requires a great amount of attention to detail along the way. An operator cannot just set a dose and hope everything works out. Water quality can change frequently, and operators must ensure they are on top of changing conditions. One way an operator can achieve this is through jar testing. This is a laboratory procedure that finds the best coagulant dose based on water quality conditions.

Figure 4.3 A Jar Test[14]

The efficiency of water treatment plants is determined by the combined effluent turbidity reading. Individual filter efficiency is also closely monitored. This will be discussed at length in the filtration chapter of the text, but it is important to have a basic grasp of that concept at this point in the treatment process. Water treatment is a lengthy process. What is occurring right now can have grave impacts down the line in the treatment process. Because of this

---

[14] Image of a jar test by Jigchen L. Norbu is licensed under CC BY-SA 4.0

consideration, jar testing and plant monitoring is more critical. Jar testing and laboratory grab sampling ensures the water, which is theoretically being treated now, will be safe when entering the distribution system hours from now.

During abnormal conditions, it is important for operators to take notes and inform senior operators and/or a supervisor. Record keeping is important because operators can go back to notes used from previous experiences. For example, a large rain event has changed the influent turbidity entering the treatment plant. A similar event happened three years prior and the influent turbidity is very similar to the ones that operators are seeing currently. Wouldn't it be nice to have a record of what the operators did three years ago? Hopefully, the operations staff from three years ago noted changes in coagulant dose, mixing speeds, chlorine demand, and other significant plant changes.

ENHANCED COAGULATION

The enhanced coagulation process is used to remove natural organic matter by adjusting the pH and coagulant dose to remove the greatest amount of suspended matter during the treatment process. The addition of acid is used to achieve the proper pH unlike sweep treatment where the operator overdoses the coagulant to achieve the correct pH range. Enhanced coagulation occurs at a lower pH. and accordingly, will see improvements in treatment such as:

- Humic and fulvic molecules separate better with lower pH. Humic and fulvic acids are organic acids commonly found in raw water sources
- Less coagulant is required for treatment
- Flocculation improves at a lower pH
- Sulfuric Acid addition before coagulant is added preconditions organic matter

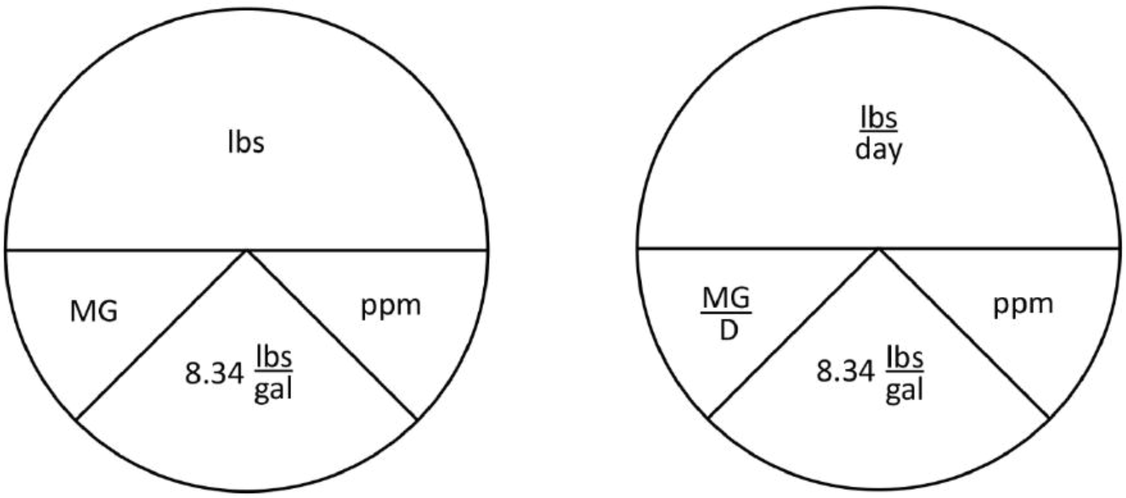
THE POUNDS FORMULA (CHEMICAL DOSAGE PROBLEMS)

One of the most important calculations an operator will use is the Pounds Formula. The pounds formula can be used to solve water math problems including milligrams per liter to pounds per day, feed rate, chlorine dosage, percent strength, and dilution calculations. The formula for the pounds calculations is:

$$\frac{\text{lbs}}{\text{day}} = \frac{\text{MG}}{\text{D}} \times \frac{8.34\ \text{lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{million parts}}$$

$$\text{lbs} = \frac{\text{MG}}{\text{D}} \times \frac{8.34\ \text{lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{million parts}}$$

Below is the pounds formula expressed in a pie wheel. The pie wheel can be used to solve a chemical dosage problem by plugging in the given information and then multiplying or dividing as indicated to determine the solution.



Example: A treatment plant will produce 2 MG a day. The chlorine dose is 3.0 mg/L. How many pounds of chlorine will the operator use?

$$\frac{\text{lbs}}{\text{day}} = \frac{\text{MG}}{\text{D}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{million parts}}$$

$$\frac{2 \text{ MG}}{\text{D}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times 3.0 \text{ mg/L} = 50.04 \frac{\text{lbs}}{\text{day}} = 50 \frac{\text{lbs}}{\text{day}}$$

It is important to note that when using the pounds formula, the water production is always expressed in MGD. For example, a problem may ask what the chlorine production is for a water treatment plant that produces 1,000,000 gallons a day. This is the easiest expression because 1,000,000 ÷ 1,000,000 = 1.

Example: A water treatment operator must super chlorinate a 650,000 gallon tank at 50 ppm. How much chlorine must the operator add?

$$\frac{\text{lbs}}{\text{day}} = \frac{\text{MG}}{\text{D}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{million parts}}$$

$$\frac{0.65 \text{ MG}}{\text{D}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times 50 \text{ ppm} = 271.05 \frac{\text{lbs}}{\text{day}} = 271 \frac{\text{lbs}}{\text{day}}$$

You must divide 650,000 gallon by one million to get 0.65 MGD to solve the equation. Round to the nearest tenth or hundredth place to get the most accurate answer. Remember you must show all work during exams to get credit, but the format is still multiple choice so be careful when rounding.

Example: The dry alum dosage rate is 15 mg/L. The daily flow rate of a treatment plant is 5 MG. How many pounds of dry alum per day is required?

$$\frac{\text{lbs}}{\text{day}} = \frac{\text{MG}}{\text{D}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{million parts}}$$

$$\frac{5 \text{ MG}}{\text{D}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times 15 \text{ mg/L} = 625.5\frac{\text{lbs}}{\text{day}} = 626\frac{\text{lbs}}{\text{day}}$$

Example: A treatment plant uses 300 lbs of alum a day. The plant output is 2,500,000 gallons a day. What is the dose?

$$\frac{\text{lbs}}{\text{day}} = \frac{\text{MG}}{\text{D}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{million parts}}$$

Step 1: Convert 2,500,000 gallons per day to MGD.

$$\frac{2{,}500{,}000 \text{ gal}}{\text{day}} \times \frac{1 \text{ MG}}{1{,}000{,}000 \text{ gal}} = \frac{2.5 \text{ MG}}{\text{day}}$$

Step 2: Solve the Pound Formula equation for ppm.

$$\frac{2.5 \text{ MG}}{\text{D}} \times \frac{8.34 \text{ lbs}}{\text{gal}} \times \text{ppm} = \frac{300 \text{ lbs}}{\text{day}}$$

$$\text{ppm} = \frac{\dfrac{300 \text{ lbs}}{\text{day}}}{2.5 \text{ MGD} \times \dfrac{8.34 \text{ lbs}}{\text{gal}}}$$

$$\text{ppm} = \frac{300}{20.85} = 14.388489 \text{ mg/L or ppm} = 14.4 \text{ mg/L or ppm}$$

Example: How many pounds of 65 % available chlorine must an operator add to a treatment plant with a dose of 3.0 mg/L and a plant output of 5 MGD?

Start the equation as you normally would. Since you are adding a solution of chlorine that is not 100 percent an extra step is needed to solve the problem. Remember, if the chlorine solution is not 100 percent available chlorine you are going to need more to dose properly!

$$\frac{\text{lbs}}{\text{day}} = \frac{\text{MG}}{\text{D}} \times \frac{8.34\ \text{lbs}}{\text{gal}} \times \frac{\text{parts}}{\text{million parts}}$$

$$\frac{5\ \text{MG}}{\text{D}} \times \frac{8.34\ \text{lbs}}{\text{gal}} \times 3.0\ \text{mg/L} = 125.1\frac{\text{lbs}}{\text{day}}$$

Next you will need to make an adjustment based on the chlorine strength.

$$\frac{125.1\frac{\text{lbs}}{\text{day}}}{0.65} = 192.4615\frac{\text{lbs}}{\text{day}} = 192.5\frac{\text{lbs}}{\text{day}}$$

If the number is smaller than your original number, you multiplied instead of dividing. You will always need more chemical if it is not 100% strength.

Example: A water tank that is 30 ft high and 100 ft in diameter must be dosed at 50 ppm for disinfection. How many pounds of 65% calcium hypochlorite must be added to dose the tank?

Step 1: Determine the volume of water in the tank.

$$\text{Volume of a Cylinder} = 0.785 \times D^2 \times H$$

$$\text{Volume} = 0.785 \times (100\ \text{ft})^2 \times 30\ \text{ft}$$

$$\text{Volume} = 235{,}500\ \text{ft}^3 \times \frac{7.48\ \text{gal}}{\text{ft}^3} = 1{,}761{,}540\ \text{gal}$$

$$1{,}761{,}540\ \text{gal} \times \frac{1\ \text{MG}}{1{,}000{,}000\ \text{gal}} = 1.76154\ \text{MGD} = 1.76\ \text{MGD}$$

Step 2: Solve the Pound Formula equation.

$$\frac{1.76\ \text{MG}}{\text{D}} \times \frac{8.34\ \text{lbs}}{\text{gal}} \times 50\ \text{ppm} = 733.92\frac{\text{lbs}}{\text{day}} = 734\frac{\text{lbs}}{\text{day}}$$

Step 3: Make an adjustment based on the calcium hypochlorite strength.

$$\frac{734\frac{\text{lbs}}{\text{day}}}{0.65} = 1{,}129.230769\frac{\text{lbs}}{\text{day}} = 1{,}129\frac{\text{lbs}}{\text{day}}$$

Key Terms

- **coagulation** – the physical and chemical reaction occurring between the alkalinity of the water and the coagulant added to the water, which results in the formation of insoluble flocs
- **flocculation** – a slow stirring process that causes the gathering together of small, coagulated particles into larger, settleable particles

CHAPTER REVIEW

1. What determines the optimal coagulant dose?
    a. chlorine test
    b. flocculation test
    c. jar test
    d. coagulation test

2. What is the most common primary coagulant?
    a. alum
    b. cationic polymer
    c. fluoride
    d. anionic polymer

3. What size are bacteria and viruses?
    a. suspended
    b. dissolved
    c. strained
    d. colloidal

4. What is the purpose of coagulation?
    a. increase filter run times
    b. increase sludge
    c. increase particle size
    d. destabilize colloidal particles

5. What is the purpose of flocculation?
    a. destabilize colloidal particles
    b. increase particle size
    c. decrease sludge
    d. decrease filter run times

6. Which are primary coagulant aids used in treatment process?
    a. poly-aluminum chloride
    b. aluminum sulfate
    c. ferric chloride
    d. All the above.

7. What does flocculation enhance?
    a. number of particle collisions to increase floc
    b. charge neutralization
    c. dispersion of chemicals in water
    d. settling speed of floc

8. If there is a problem with floc formation, what would you consider changing?
    a. adjust coagulant dose
    b. stay the course
    c. adjust mixing intensity
    d. both A & C

9. Which step in the treatment process is the shortest?
    a. filtration
    b. sedimentation
    c. flocculation
    d. coagulation

10. To lower the pH for enhanced coagulation, what will the operator add?
    a. chlorine
    b. sulfuric acid
    c. lime
    d. caustic soda

11. How long does the flocculation process last?
    a. seconds
    b. 5-10 minutes
    c. 15-45 minutes
    d. over an hour

12. A treatment plant has a maximum output of 30 MGD and doses ferric chloride at 75 mg/L. How many pounds of ferric chloride does the plant use in a day?
    a. 18,765
    b. 17,765
    c. 19,765
    d. 16,765

13. A treatment plant uses 750 pounds of alum a day as it treats 15 MGD. What was the dose rate?
    a. 4 mg/L
    b. 5 mg/L
    c. 6 mg/L
    d. 7 mg/L

14. A treatment plant operates at 1,500 gallons a minute and uses 500 pounds of alum a day. What is the alum dose?
    a. 18 mg/L
    b. 28 mg/L
    c. 8 mg/L
    d. 38 mg/L

CHAPTER 5 – SEDIMENTATION

Sedimentation is the third step in a conventional treatment process. It occurs after coagulation and flocculation and before filtration. **Sedimentation** removes suspended solids with the use of gravity by slowing the flow of water down to allow material to settle. The settleable solids fall to the bottom of the sedimentation basin reducing the load on the filtration process. A sedimentation basin acts like a lake in the sense that it allows particles to settle naturally. Deeper lakes have much higher quality water entering the treatment plant because the water can "settle" for a longer period. Treatment plants which use imported water from higher turbidity water sources may be required to use conventional treatment with sedimentation for efficient treatment.

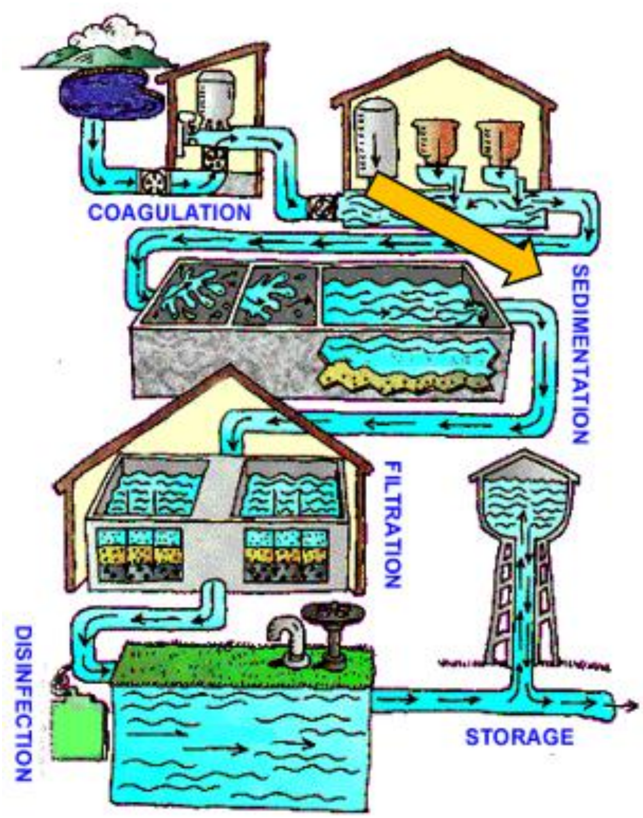


Figure 5.1: The Water Treatment Process[15]

After this chapter, you should be able to:

- explain sedimentation process;
- identify zones of sedimentation basin;
- describe types of sedimentation basins; and
- solve velocity and detention time problems.

[15] Image of water treatment by the EPA is in the public domain.

FACTORS AFFECTING SEDIMENTATION

Several factors can affect the sedimentation process, including physical and environmental conditions. Increased pretreatment may be necessary when adverse conditions are present. Factors that affect the sedimentation process include the shape and size of particles, the density of particles, water temperature, particle charge, dissolved substances in the water, environmental effects, and characteristics of the basin.

As discussed in the previous chapter, smaller particles do not settle out easily and their size must be increased with coagulation and flocculation. The larger, denser particles created are called floc. Particles greater than .01 millimeters will settle in the sedimentation process. The shape of particles is also a consideration. Smoother particles with less jagged edges settle out quicker and easier.

Temperature decreases will cause the settling rate to decrease. The settling rate or velocity decreases when the water temperature is colder. Chemical dosage rates need to be adjusted during colder periods of the year or lower flows are necessary in the flocculation basins. There are three types of currents in a sedimentation basin: surface, density, and eddy. Surface currents are caused by wind while density currents are caused by temperature differences and the concentration of solids. Eddy currents are caused by the influent and effluent flow of water in the sedimentation basin. Currents can be beneficial as they can help to promote the building of floc, but they can also cause uneven disbursements of solids throughout a sedimentation basin reducing the efficiency.

SEDIMENTATION ZONES

The four zones of a Sedimentation basin include:

1. **inlet zone**: where the water enters from the flocculation basin, water is distributed evenly throughout the sedimentation basin to prevent short circuiting; short circuiting occurs when water entering a treatment process tank or basin quickly moves from influent to effluent reducing the waters detention time in a given process
2. **settling zone**: the largest part of a sedimentation basin, the water will stay here undisturbed for three or more hours while particles settle to the bottom.
3. **sludge zone**: located at the bottom of the settling zone, it is where settled particles collect in the form of sludge. Velocities at the bottom of the sludge zone should be minimized to prevent solids from re-suspending.
4. **outlet zone**: the location where water enters a channel or conduit.

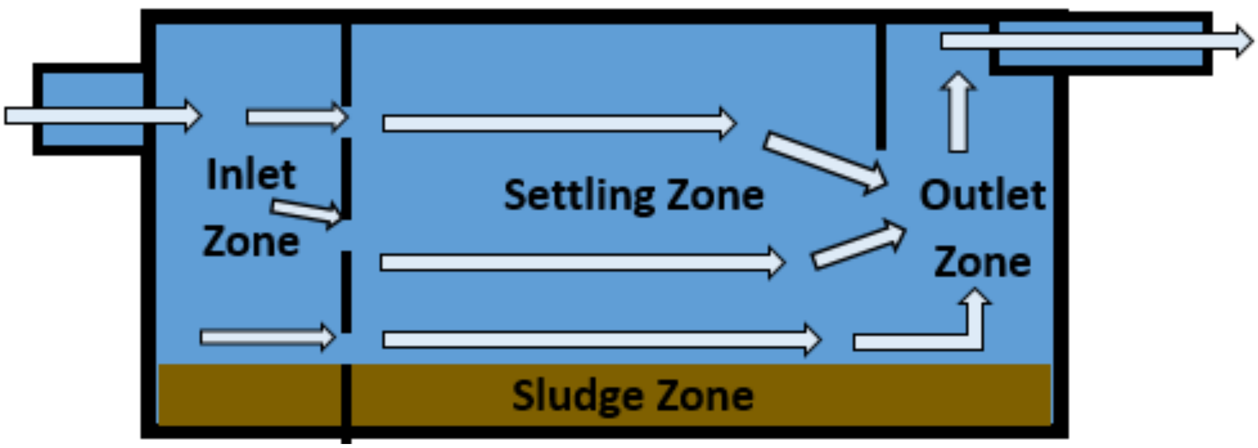


Figure 5.2 Sedimentation Zones[16]

TYPES OF SEDIMENTATION BASINS

There are several different types of basin designs available for engineers and planners when building a water treatment facility. Rectangular basins are typically found at large scale water facilities because of their predictable treatment and high tolerance to turbidity, color, and algae. They are cost efficient, require lower maintenance, and have less short circuiting issues. The figure above representing the different zones of a sedimentation basin is an example of a rectangular sedimentation basin.

Circular and square basins are used in areas where space is limited. They are sometimes called clarifiers and are subject to short circuiting in the corners. The circular variety can also include up flow clarifiers or solids contact clarifiers. In these types of clarifiers, the coagulation, flocculation, and sedimentation process all occur in the same basin or clarifier.

[16] Image by COC OER is licensed under CC BY

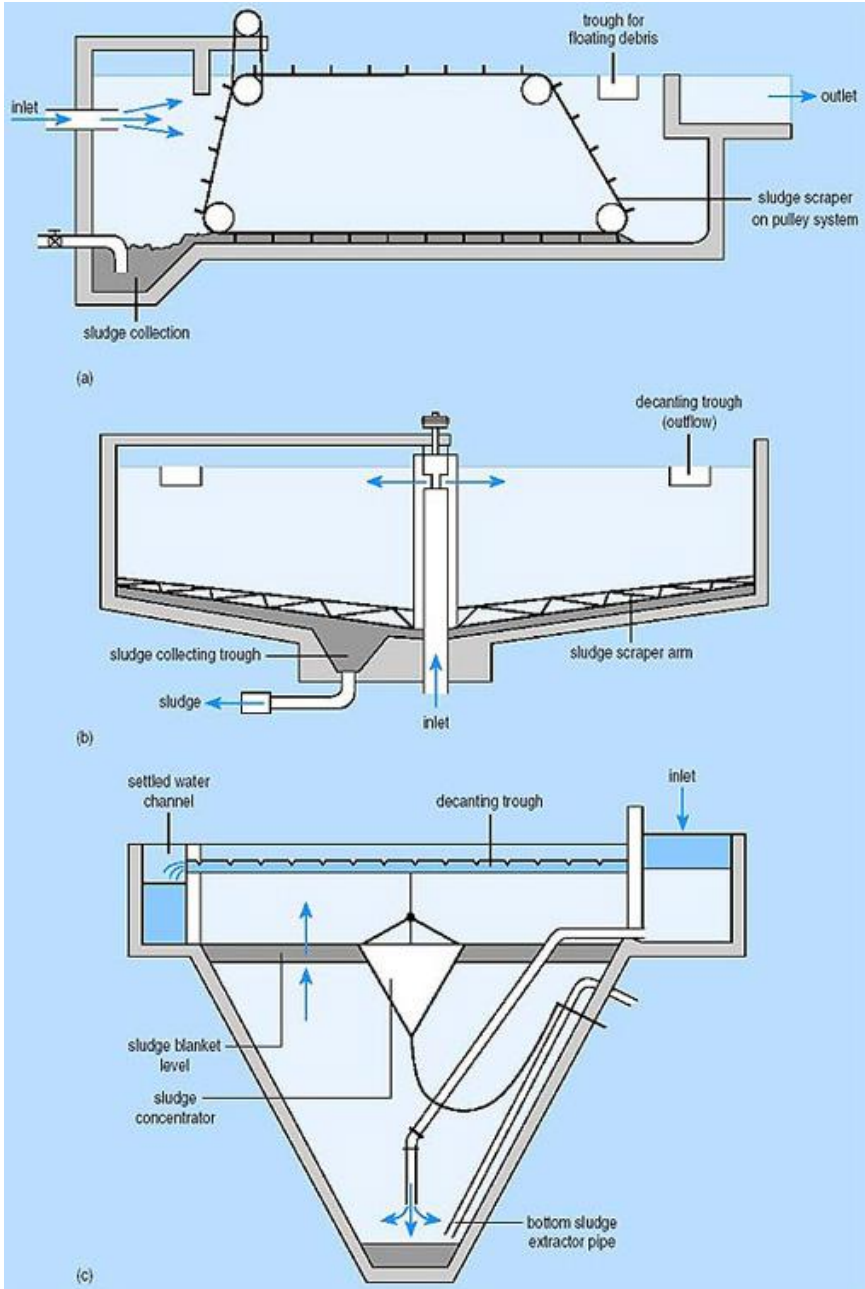


Figure 5.3: Typical sedimentation tanks: (a) rectangular horizontal flow tank; (b) circular, radial-flow tank; (c) hopper-bottomed, upward flow tank –[17]

DETENTION TIME

Detention time is the amount of time it takes water to travel through a tank or sedimentation basin. It is also referred to as retention time. You will hear some operators use the terms CT and contact time interchangeably, but it is incorrect. The term CT will be discussed in greater

[17] Image by The Open University is licensed under CC BY-NC-SA

detail in Chapter 7. Detention time can be used to solve equations for time and flow. Formulas for both types of equations are listed below:

$$D_t = \frac{\text{Volume}}{\text{Flow}}$$

Units are extremely important when using this formula. There are three variables in this formula: Detention Time, Flow, and Volume. Each variable can be provided using a variety of units. Here are some examples for each.

Detention Time – seconds, minutes, hours, days

Flow – cubic feet per second, gallons per minute, million gallons per day

Volume – cubic feet, gallons, million gallons

Note that when using the detention time formula, all of the units must align in order to solve the equation. If the units are similar (matching), then dividing volume by flow will yield a time (Detention Time). However, simply dividing a volume by a flow will not result in a time. For example, if you divide gallons by cubic feet per second there is no resulting answer. This is because "gallons" and "cubic feet" will not cancel each other.

When solving for Detention Time, the units for Volume and Flow must match. Solving for Detention Time is not the only variable to solve for with this formula. If Detention Time and Volume are given, then you will be solving for Flow. Similarly, if Detention Time and Flow are given, then you will be solving for Volume. In all of these examples, the units must be similar in order to cancel out and yield your answer.

Remember, that even when your units align, the calculation may not provide your answer in hours, the most common way to express Detention Time. Read each question carefully and always convert your answer to the units specified in the question.

Example: A rectangular sedimentation basin is 80 ft long by 25 ft wide and is 25 ft deep. The flow per day is 2.0 MGD. What is the detention time in hours?

Step 1: Determine the volume of the basin in gallons.

$$\text{Volume} = L \times W \times H$$

$$\text{Volume} = 80\text{ ft} \times 25\text{ ft} \times 25\text{ ft} = 50{,}000\text{ ft}^3$$

$$50{,}000\text{ ft}^3 \times \frac{7.48\text{ gal}}{\text{ft}^3} = 374{,}540\text{ gal}$$

Step 2: Calculate the detention time.

$$D_t = \frac{\text{Volume}}{\text{Flow}}$$

$$D_t = \frac{374{,}000 \text{ gal}}{2{,}000{,}000 \text{ gal/day}} = 0.187 \text{ days}$$

Step 3: Convert days to hours.

$$D_t = 0.187 \text{ days} \times \frac{24 \text{ hours}}{1 \text{ day}} = 4.488 \text{ hours} = 4.5 \text{ hours}$$

More complicated problems will have you solve for hours and minutes. Keep this in mind for future math equations that ask for more information.

$$0.5 \text{ hours} \times \frac{60 \text{ mins}}{1 \text{ hr}} = 30 \text{ minutes}$$

Example: A circular basin is 100 ft in diameter. The basin is 25 ft deep and has a detention time of 4 hours. What is the flow per day?

Step 1: Determine the volume of the basin in gallons.

$$\text{Volume} = 0.785 \times D^2 \times H$$

$$\text{Volume} = 0.785 \times (100 \text{ ft})^2 \times 25 \text{ ft} = 196{,}250 \text{ ft}^3$$

$$196{,}250 \text{ ft}^3 \times \frac{7.48 \text{ gal}}{\text{ft}^3} = 1{,}467{,}950 \text{ gal}$$

Step 2: Solve the detention time equation for flow.

$$D_t = \frac{\text{Volume}}{\text{Flow}}$$

$$\text{Flow} = \frac{\text{Volume}}{D_t} = \frac{1{,}467{,}950 \text{ gal}}{4 \text{ hours}} \times \frac{24 \text{ hour}}{1 \text{ day}} = \frac{8{,}807{,}700 \text{ gal}}{\text{day}}$$

Step 3: Convert your answer to MGD.

$$\frac{8{,}807{,}700 \text{ gal}}{\text{day}} \times \frac{1 \text{ MG}}{1{,}000{,}000 \text{ gal}} = 8.8077 \text{ MGD} = 8.8 \text{ MGD}$$

SLUDGE HANDLING AND REMOVAL

Sludge that collects at the bottom of a sedimentation basin must be removed from time to time for several reasons. As discussed earlier in the chapter, sludge can become re-suspended after settling creating greater load on the downstream filter. Next, sludge buildup can cause the water source to become septic. In this scenario, microbiological growth occurs when oxygen supplies are depleted. Septic conditions can cause taste and odor problems in treated water and require more chlorine during the disinfection process. Finally, the more sludge that builds up leads to decreased detention time because there is less area for the water to travel and for solids to settle out.

Larger plants will have to remove sludge at a greater rate and with the assistance of sludge removal equipment. Smaller plants may be able to remove sludge manually with portable sanitary pumps and squeegees and hoses to complete cleanup. The amount of time between cleanups can vary with the quality of the water source and the amount of water being treated. Consequently, shutdowns for sludge clean-up will vary dramatically from treatment plant to treatment plant.

Sludge removal equipment includes mechanical rakes, drag-chain, and flights, and traveling bridges. The chain and flight system is used in rectangular basins. A chain with scrappers attached moves across the bottom of the basin collecting sludge and moving it to a sump. This system works well but has several moving parts. Additionally, the basin must be dewatered to perform maintenance. The traveling bridge system is also used in a rectangular basin. It travels the entire length of the basin. A pump is attached to the bottom of the system and sludge is pumped to a trough just below the top of the sedimentation basin. The bridge system is easier to perform maintenance on because the parts can be removed from the basin; therefore, dewatering the entire basin is not required. Finally, mechanical rakes are used in rectangular or circular basins. A rake spans the entire length of the basin while spinning around the basin. Sludge is moved into a trough which can be pumped out or moved by gravity to a sludge collection tank.

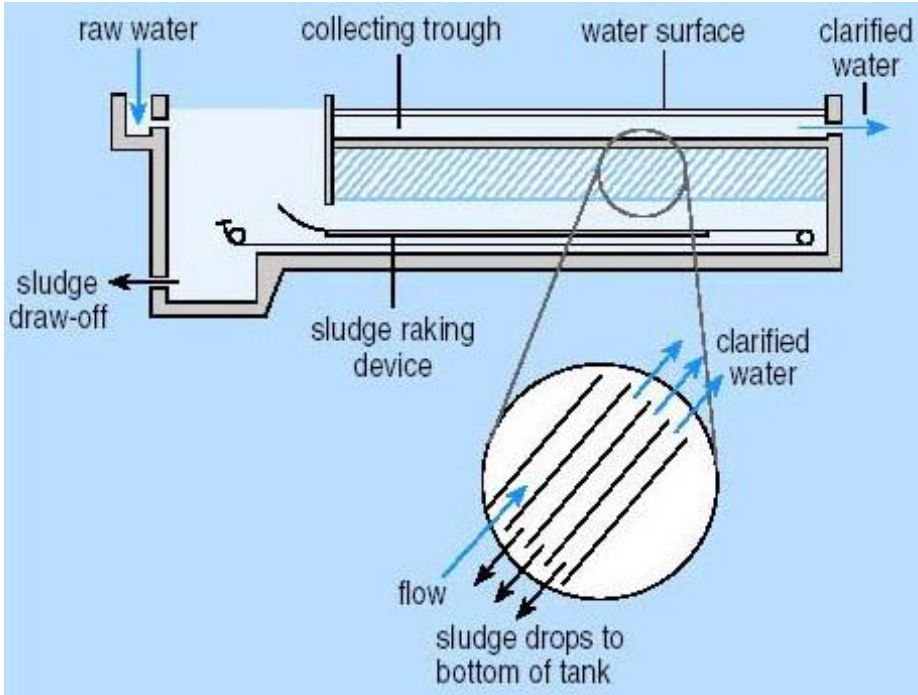


Figure 5.4: Mechanical Rake Filter[18]

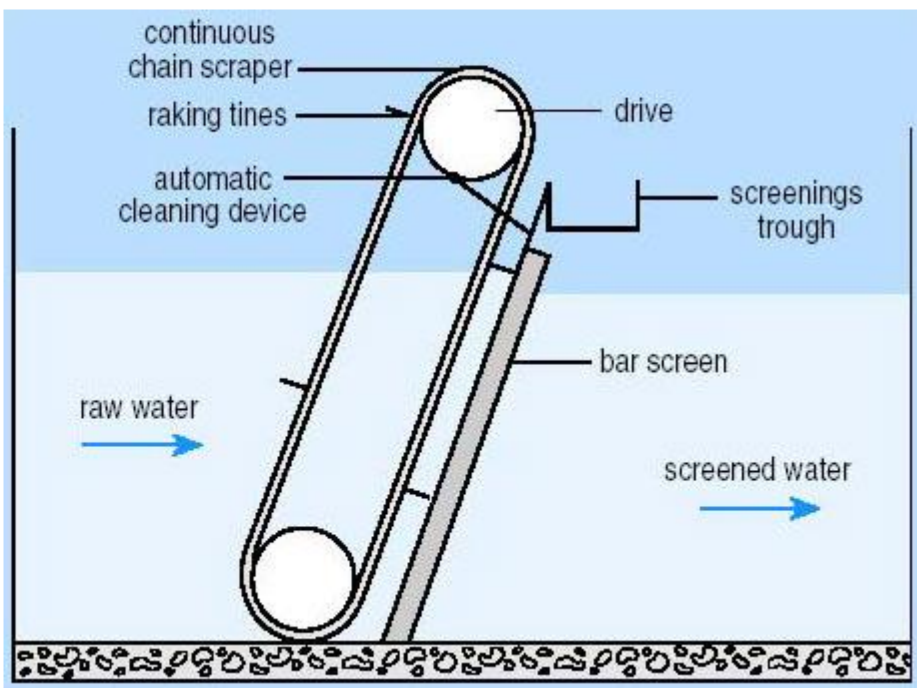


Figure 5.5: Sludge Removal Screen[19]

[18] Image by The Open University is licensed under CC BY-NC-SA
[19] Image by The Open University is licensed under CC BY-NC-SA

REVIEW AND DAILY OPERATIONS OF SEDIMENTATION BASINS

In review, the purpose of sedimentation is to allow suspended solids to settle through the physical process of gravity. The flow of water is slowed down to allow settling to occur. During the process, sedimentation can remove 95% or more of the total solid material operators remove during the entire water treatment process.

Water treatment plants with low turbidity or fewer than 10 turbidity units may find direct filtration or clarification to be a more cost effective process. A reoccurring theme that should be noted throughout the text is the fact that all treatment facilities are different and the factor that dictates plant processes including facility building and day to day operation is the source water.

The settling characteristics of suspended material dictates how well sedimentation performs. Flow rate through the sedimentation basin drives performance as well as the control of sludge. High flow rates cause solids to carry over and could also impact the sludge at the bottom of the sedimentation basin. Operators must perform regular jar testing and laboratory testing as well as operate sedimentation basins based on the designed capacity of the basin to ensure optimal performance. Improper operation of sedimentation basins will lead to increased load on downstream filters resulting in early filter washes, increased disinfectant use, and possibly tier violations.

VELOCITY MATH

The movement of water is obviously an important thing to know if you are a water treatment operator. Flow rates can be used to determine dosage rates, to identify daily averages, to dewater pipelines, to fill pipelines, and for future planning of distribution and treatment equipment.

To solve a flow problem, you need the diameter of the pipe and the velocity of the water (or liquid) in the pipe.

Flow rate is expressed as volume over time.

$$\text{Flow Rate} = \frac{\text{Volume}}{\text{Time}}$$

The units for volume can be provided as gallons, million gallons, cubic feet or any other volume unit. The units of time can be given as seconds, minutes, hours, etc. However, when solving for Flow Rate, Q, always use the units cubic feet per second, expressed as:

$$Q = \frac{\text{Volume}}{\text{Time}} = \frac{\text{cubic feet}}{\text{sec}} = \frac{\text{ft}^3}{\text{sec}}$$

In order to calculate a Flow Rate, you need to know the area of the vessel that the liquid is traveling through and the velocity it is traveling. The formula for Flow Rate is

$$\text{Flow Rate (cfs)} = \text{Area (ft}^2) \times \text{Velocity (ft/sec)} \rightarrow Q = A \times V$$

Remember the formulas for area are:

$$\text{Circle} = 0.785 \times D^2 \qquad \text{Rectangle} = L \times W \qquad \text{Trapezoid} = \frac{b_1 + b_2}{2} \times H$$

And velocity is expressed as:

$$\text{Velocity (ft/sec)} = \frac{\text{Distance (ft)}}{\text{Time (sec)}}$$

The units for area should always be in square feet and the units for velocity should always be in feet per second. Therefore, the flow rate equation should look like this:

$$\text{Flow Rate (cfs)} = \text{Area (ft}^2) \times \text{Velocity (ft/sec)} \rightarrow Q = A \times V$$

$$\frac{\text{cubic feet}}{\text{second}} = \frac{\text{ft}^2}{1} \times \frac{\text{ft}}{\text{second}} \rightarrow \frac{\text{ft} \times \text{ft} \times \text{ft}}{\text{second}} = \frac{\text{ft} \times \text{ft}}{1} \times \frac{\text{ft}}{\text{second}}$$

$$\text{Flow Rate (cfs)} = \text{Area (ft}^2) \times \text{Velocity (ft/sec)} \rightarrow Q = A \times V$$

A velocity problem occurs when the known value is the pipe diameter and flow rate of pipe.

$$\text{V(Velocity)} = \frac{\text{Q(Flow Rate)}}{\text{A(Area)}}$$

Finally, pipe size is used when the known values are the pipe flow rate and velocity.

$$\text{A(Area)} = \frac{\text{Q(Flow Rate)}}{\text{V(Velocity)}}$$

Proper use of dimensional analysis is critical when attempting to solve velocity equations. These types of problems often take multiple steps because answers need to be converted to the appropriate units based on the situation.

Example: A pipeline is 18” in. diameter and flowing at a velocity of 125 ft per minute. What is the flow in gallons per minute?

Step 1: Convert the pipeline diameter to feet.

$$\frac{18 \text{ in}}{1} \times \frac{1 \text{ ft}}{12 \text{ in}} = 1.5 \text{ ft}$$

Step 2: Calculate the flow rate.

$$\text{Q (Flow Rate)} = \text{A(Area)} \times \text{V(Velocity)}$$

$$\text{Q (Flow Rate)} = 0.785 \times (1.5 \text{ ft})^2 \times \frac{125 \text{ ft}}{\text{min}} = \frac{220.78125 \text{ ft}^3}{\text{min}}$$

Step 3: Convert to gpm.

$$\frac{220.78125 \text{ ft}^3}{\text{min}} \times \frac{7.48 \text{ gal}}{\text{ft}^3} = 1{,}651.44375 \text{ gpm} = 1{,}651 \text{ gpm}$$

Example: The flow of a pipe is 2,000 gallons per minute. The diameter of the pipe is 24”. What is the velocity of the pipe in ft per minute?

Step 1: Convert the pipeline diameter to feet and the flow rate from gpm to cf per min.

$$\frac{24 \text{ in}}{1} \times \frac{1 \text{ ft}}{12 \text{ in}} = 2 \text{ ft}$$

$$\frac{2{,}000 \text{ gal}}{\text{min}} \times \frac{\text{ft}^3}{7.48 \text{ gal}} = \frac{267.3796 \text{ ft}^3}{\text{min}} = \frac{267 \text{ ft}^3}{\text{min}}$$

Step 2: Calculate the velocity.

$$\text{V(Velocity)} = \frac{\text{Q(Flow Rate)}}{\text{A(Area)}}$$

$$\text{V(Velocity)} = \frac{\frac{267\ \text{ft}^3}{\text{min}}}{0.785 \times (2\ \text{ft})^2} = \frac{\frac{267\ \text{ft}^3}{\text{min}}}{3.14\ \text{ft}^2} = \frac{85.0318\ \text{ft}}{\text{min}}$$

$$\text{V(Velocity)} = 85\ \text{ft per min}$$

Example: The velocity in a pipeline is 2 ft/sec. and the flow is 3,000 gpm. What is the diameter of the pipe in inches?

Step 1: Convert the flow rate units to match the velocity units.

$$\frac{3{,}000\ \text{gal}}{\text{min}} \times \frac{\text{ft}^3}{7.48\ \text{gal}} \times \frac{1\ \text{min}}{60\ \text{sec}} = \frac{6.68\ \text{ft}^3}{\text{sec}}$$

Step 2: Calculate the area.

$$\text{A(Area)} = \frac{\text{Q(Flow Rate)}}{\text{V(Velocity)}}$$

$$\text{A(Area)} = \frac{\frac{6.68\ \text{ft}^3}{\text{sec}}}{\frac{2\ \text{ft}}{\text{sec}}} = 3.34\ \text{ft}^2$$

Step 3: Calculate the diameter of the pipe using the equation for the area of a circle.

$$\text{Area of a Circle} = 0.785 \times D^2$$

$$D^2 = \frac{\text{Area}}{0.785} = \frac{3.34\ \text{ft}^2}{0.785} = 4.25477\ \text{ft}^2$$

$$\sqrt{D^2} = \sqrt{4.25477\ \text{ft}^2}$$

$$D = 2.06271\ \text{ft} = 2\ \text{ft}$$

Step 4: Convert the pipe diameter to inches.

$$\frac{2\ \text{ft}}{1} \times \frac{12\ \text{in}}{1\ \text{ft}} = 24\ \text{in}$$

Key Terms

- **detention time** – the amount of time it takes water to travel through a tank or sedimentation basin
- **flocculation** – a slow stirring process that causes the gathering together of small, coagulated particles into larger, settleable particles
- **inlet zone** – the location in the sedimentation basin where the water enters from the flocculation basin
- **outlet zone** – the location in the sedimentation basin where the water enters a channel or conduit
- **sedimentation** – the process that removes suspended solids with the use of gravity by slowing the flow of water down to allow material to settle
- **settling zone** – the location in the sedimentation basin where water will stay undisturbed for three or more hours while particles settle to the bottom
- **sludge zone** – the location in the sedimentation basin where settled particles collect in the form of sludge

CHAPTER REVIEW

1. Which is the treatment process that involves coagulation, flocculation, sedimentation, and filtration?
    a. direct filtration
    b. slow sand filtration
    c. conventional treatment
    d. pressure filtration

2. What is the name for the waste produced by sedimentation?
    a. backwash water
    b. sludge
    c. wastewater
    d. mud

3. What kind of process is sedimentation?
    a. physical
    b. chemical
    c. biological
    d. direct

4. What does sedimentation do in water treatment plants?
    a. settle pathogenic material
    b. destabilize particles
    c. disinfect water
    d. reduce loading on filters

5. How does scouring affect conditions in a sedimentation tank?
    a. could impact the rest of treatment process
    b. higher flow rates in the sludge zone
    c. re-suspends settle sludge
    d. all of the above

6. What are the four zones in a sedimentation basin?
    a. inlet, sedimentation, sludge, outlet
    b. inlet, filter, waste, outlet
    c. inlet, top, bottom, outlet
    d. surface, sedimentation, sludge, outlet

7. What might cause short circuiting in a sedimentation basin?
    a. surface wind
    b. ineffective weir placement, or weirs covered in algae
    c. poor baffling in sedimentation inlet zone
    d. all of the Above

8. What percent of solids should be removed during sedimentation?
    a. 95% or more
    b. 80-95%
    c. 70-80%
    d. 60-70%

9. What type of basin includes coagulation and flocculation?
    a. rectangular
    b. triangular
    c. up-flow
    d. none of the above

CHAPTER 6 – FILTRATION

Filtration is the final and most important removal requirement required by the Surface Water Treatment Rule (SWTR). During filtration, water passes through material such as sand, gravel, and anthracite coal to remove floc and disease-causing microorganisms from the finished water. Filtration is the process where suspended colloidal particles are removed from the water. Along with removing possible pathogenic material in the water, removal of turbidity is also achieved which could hide pathogenic organisms and add color to the finished water.

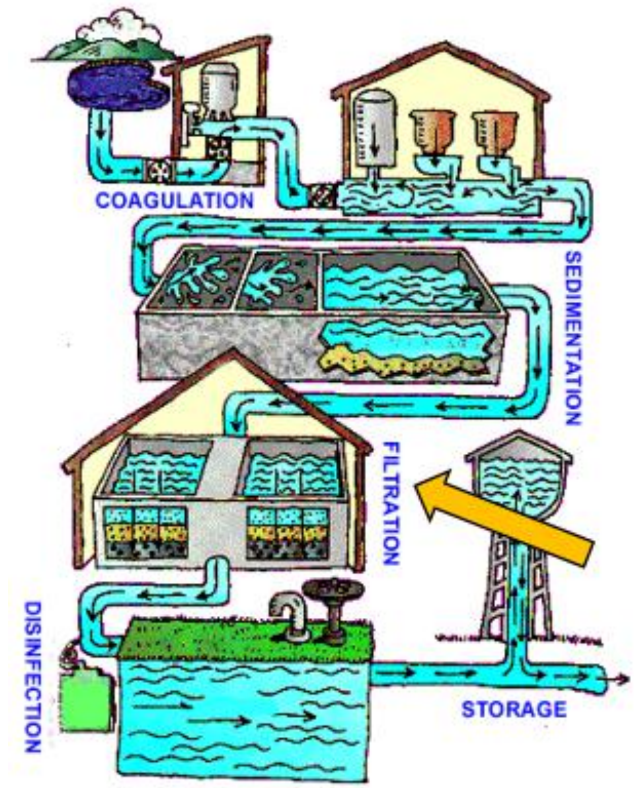


Figure 6.1: The Water Treatment Process[20]

After reading this chapter, you should be able to:

- describe treatment technologies;
- differentiate among filter media configurations and types;
- explain the process of backwashing; and
- solve math problems relating to filtration.

The SWTR sets forth guidelines for all public water agencies that use surface water as a source. Surface water was covered in Chapter One and is any water open to atmosphere that is

[20] Image of water treatment by the EPA is in the public domain.

susceptible to runoff. The minimum requirements for treatment are disinfection, but most water sources do not meet these very stringent guidelines.

The effectiveness of filtration is based on several important factors. Proper filtration occurs based on incoming source water quality. For example, a storm event near the source water could case higher incoming turbidity than the treatment plant is used to handling. Operational changes such as washing filters may be required. The physical and chemical characteristics of suspended material also come into play during treatment. Too much or too little chemical can lead to ineffective filtration. To follow the storm event example, an operator may need to make changes to coagulant and polymer doses to account for increased turbidity and particulate entering the treatment plant. Finally, the type of filtration used by a treatment facility is also very important. This decision is mostly out of operators' hands as engineers and water quality experts will decide what the most effective treatment process is for the source water before building a treatment facility.

In the photo below is a filter in normal operation.

Figure 6.2: Public Agency Filtration[21]

[21] Photo provided by author

TREATMENT TECHNOLOGIES

There are four approved treatment technologies in the United States. The most widely used treatment technologies include conventional treatment, direct filtration, diatomaceous earth treatment, and slow sand filtration.

Slow sand filtration facilities are becoming less common because of the large amount of time it takes to treat water and the large amount of space the facilities require. The filtration rates for slow sand filtration are .05 to .10 GPM/sq. foot. Particles are adsorbed in a chemical layer known as a **schmutzdecke**. After an amount of time, the biological layer must be manually removed by an operator or maintenance staff. The slow time and intensive labor make this treatment method the least ideal especially in areas with larger populations.

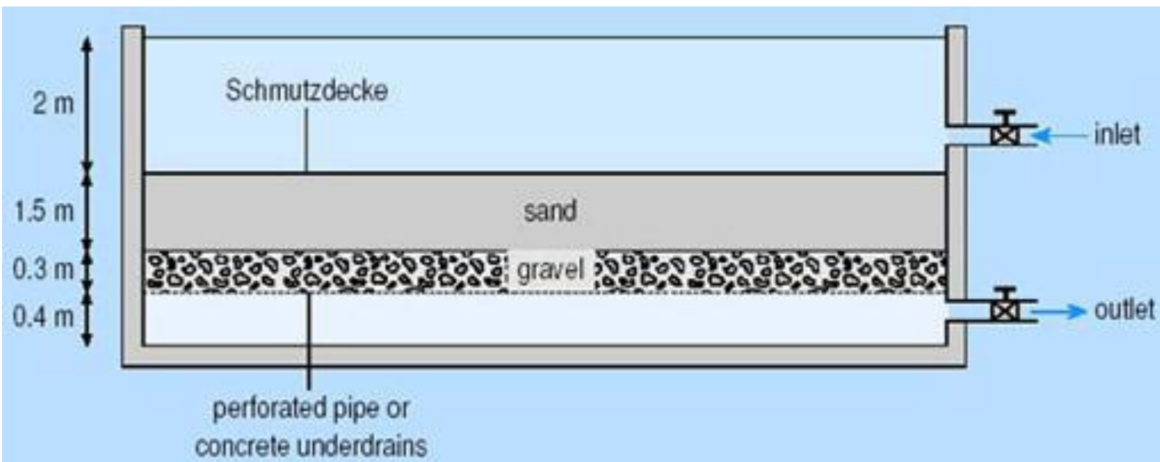


Figure 6.3: Slow Sand Filtration[22]

Diatomaceous earth filtration is accomplished through pressure filtration. It can also be referred to as precoat filtration. The filter media is added as slurry to the treatment vessel. Within the vessel, lays a pipe known as a septum. The slurry attaches itself to the septum and water is run through the vessel where pathogenic and suspended material is captured and strained out of the finished water. This kind of treatment process is very common for swimming pool treatment and beverage companies. This type of treatment method is generally not used by larger municipalities because of the large amount of disposal of sludge and the continuous purchasing of filter media.

[22] Image by The Open University is licensed under CC BY-NC-SA

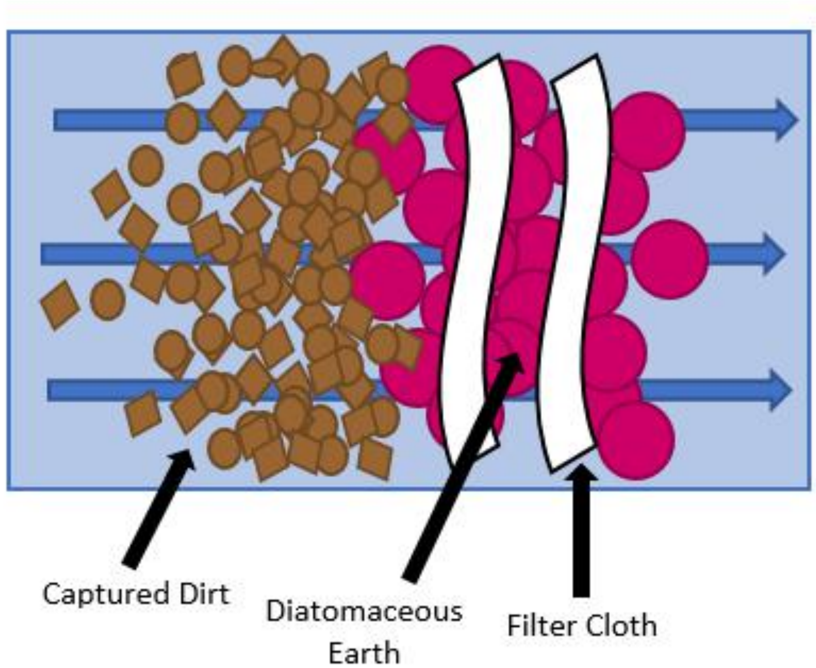


Figure 6.4: Diatomaceous Earth Filter[23]

Gravity filtration is comprised of the final two approved Water Treatment technologies. Direct Filtration and conventional treatment are the most widely used treatment technologies in the United States. They are described as gravity filtration because the head pressure of the water forces the water to travel through filtered media to remove impurities from the drinking water. **Direct Filtration** differs from conventional treatment because the sedimentation process is skipped. Areas with source water higher in quality may opt for direct filtration to reduce costs and the amount of land space for sedimentation basins can be substantial. The average filtration rate for gravity filtration beds is 3.0 GPM/sq. ft- 6.0 GPM/ sq. ft.

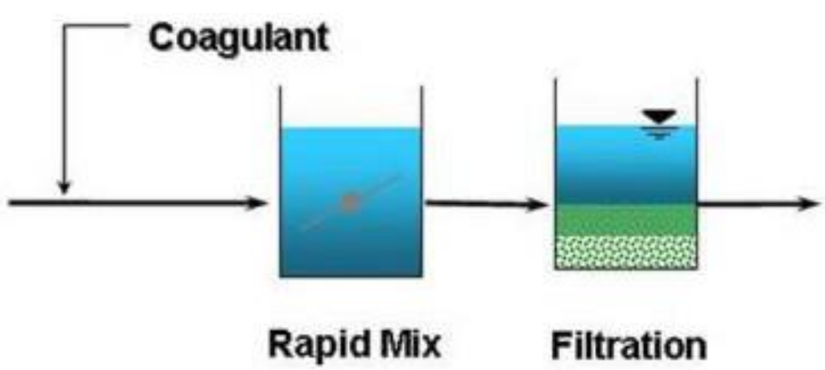


Figure 6.5: Direct Filtration[24]

[23] Image by COC OER is licensed under CC BY
[24] Image by the EPA is in the public domain

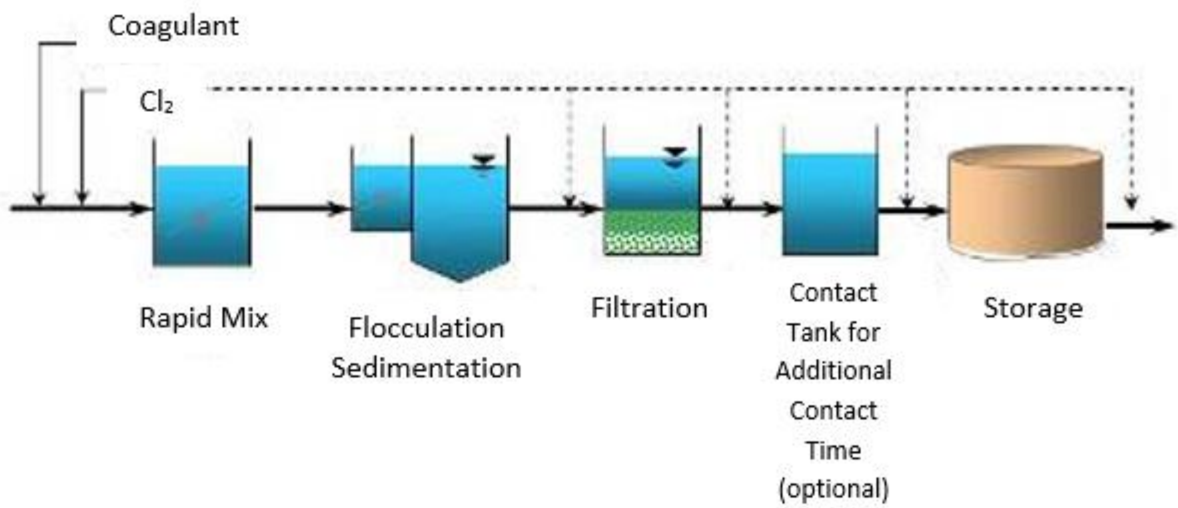


Figure 6.6: Conventional Treatment[25]

Alternative treatment plant methods can be approved on a case by case basis. Newer technologies such as membrane filtration and reverse osmosis have been utilized as the technology has improved and the costs associated with running these operations have decreased. Santa Clarita Valley Water utilizes an alternative technology known as Upflow Clarification. SCV Water can use this technology because of the very low turbidity levels in the water provided by Castaic Lake. It is a more condensed version of conventional treatment and requires much less space due to the lack of sedimentation basins.

FILTER MEDIA

The types of media used in gravity filters are sand, anthracite coal and garnet. Garnet is a reddish colored mineral sand with a density that is greater than sand. Gravel is also used as a filter under layer below the filter media being used. It must be heavier than the filter media, so it is able to settle back under media after a completed filter wash cycle.

When choosing filter media, it is important to select media which has good hydraulic characteristics, is durable, has no impurities, is insoluble in water, will not dissolve, and does not react with constituents in the water supply. Media is classified by four parameters including its effective size, uniform efficiency, specific gravity, and the hardness of the media. The effective size is the sieve opening in the media that allows water to pass through while collecting the impurities in water. 90 percent of the particles must be bigger than the opening to filter out particles.

When deciding what kind of media to choose for the filer it is important to consider the amount of time it takes for filter turbidity to break through. For example, you operate a treatment plant that requires individual filters say below 0.3 NTU (or Nephelometric Turbidity Units). Once an

[25] Image by the EPA is in the public domain

individual filter goes above this limit it must be washed. Secondly, head loss must be a consideration. Head loss occurs after material builds up over time during the filtration process. The head loss will cause longer filtration times and cause the filter level to rise. Once a filter reaches terminal head loss it must be back washed. The media is not always the cause of head loss and turbidity break through. Improper dosage can cause the head loss and breakthrough.

The uniform coefficient is the ratio between the different sizes of media comprised in the filter bed. The lower the uniform coefficient means the media is closer to the same size than if it were higher. The lower the efficiency number adds to the cost of the media.

Filter production is the amount of water that a given filter can produce in a day. This flow is usually accounted for in Million Gallons per Day (MGD). Individual filtration rates are calculated by dividing the flow rate of the filter in gallons per minute by the surface area of a filter. The filtration rate for gravity filters can be between 2gpm-10gpm/ square foot. This topic will be discussed in more detail during the math portion of this chapter.

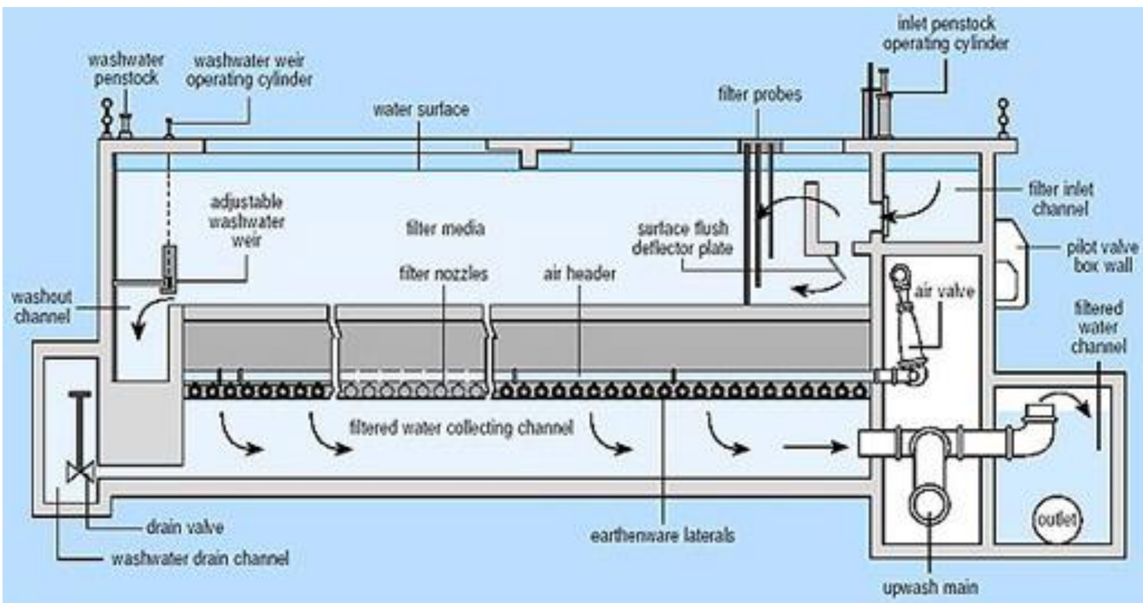


Figure 6.7: Rapid gravity sand filter[26]

[26] Image by The Open University is licensed under CC BY-NC-SA

Table 6.1: Filter Media Types

Gravel[27]

Sand[28]

Garnet[29]

Anthracite[30]

There are several different types of media configurations. Filtration plants can utilize monomedia, dual media, and multimedia configurations. A monomedia plant has only one type of media which could be coarse sand or anthracite coal. Single media filters may have to be washed more frequently as they tend to be smaller and have more frequent head loss issues. Dual media filters consist of a lower sand level and an upper anthracite layer with larger diameter pores that allow deeper solids penetration. Finally, multimedia filters are used in pressure vessel treatment applications. Multimedia filters have sand, anthracite, and an upper garnet layer. The drawback to pressure vessels is the inability to view filter media within the pressure vessel.

FILTER OPERATION AND BACKWASHING FILTERS

Throughout the chapter the subject of “washing” has come up. Filter run times are dependent on three factors but first it is important to know how filter efficiency is measured. The efficiency of a filter is measured by the filter effluent turbidity. And the overall plant efficiency measures the combined effluent turbidity of all the filters. Improper coagulation and filtration could lead to turbidity spikes and in the worst case scenario could lead to a public health crisis.

Pictured on the following page is a photo of a typical filter deck at a water treatment plant.

[27] Image by Martin Olsson is licensed under CC BY-SA 3.0
[28] Image by Yug is in the public domain
[29] Image by Siim is licensed under CC BY-SA 4.0
[30] Image is in the public domain

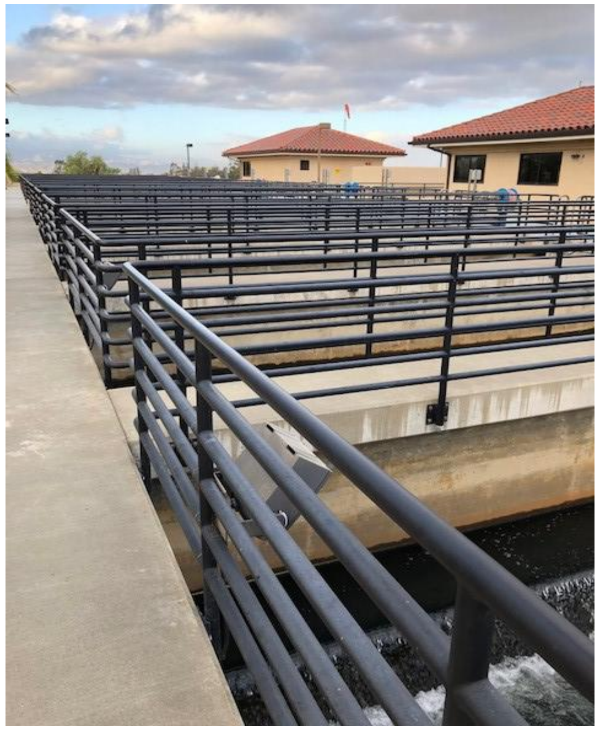


Figure 6.8: Filter Deck[31]

The first factor that an operator uses to determine whether a filter wash is necessary is the individual filter turbidity. Each treatment plant will have its own operating conditions and permits to follow. If an individual filter fails to meet the turbidity goals or limits, the filter must be put in a backwash cycle. Filters that continue to have decreased run times may need a filter profile ran to figure out why the filters are not meeting standards.

High head loss is the second factor that will lead to a filter wash. After the filter is used for a certain period it becomes clogged with the solids the filter is removing. This condition will also lead to increased turbidity as the solids that should be getting captured “breakthrough” the effluent into the treated water supply. Finally, a filter wash will be performed after a certain period no matter what the operating conditions are. This is the ideal scenario for washing a filter.

The **backwash procedure** is the reverse flow of water through the filter. This process removes solids from the filter after breakthrough or the filter run time is hit. Operators must operate the backwash rates at an optimal range because inadequate rates will not properly remove the solids from the filter and excessive rates can cause mud balls and mounds to form within the filter.

Washed water can be recycled by sending the waste stream to collection basins. The water can then be returned to the head works of the plant and be mixed with raw water to be treated

[31] Photo provided by author.

again. The filter backwash rule limits the amount of water that can be returned into the head works of the plant at a given time. Returning too much recycled water could increase the chances of allowing microorganisms such as *Cryptosporidium* into the treatment plant.

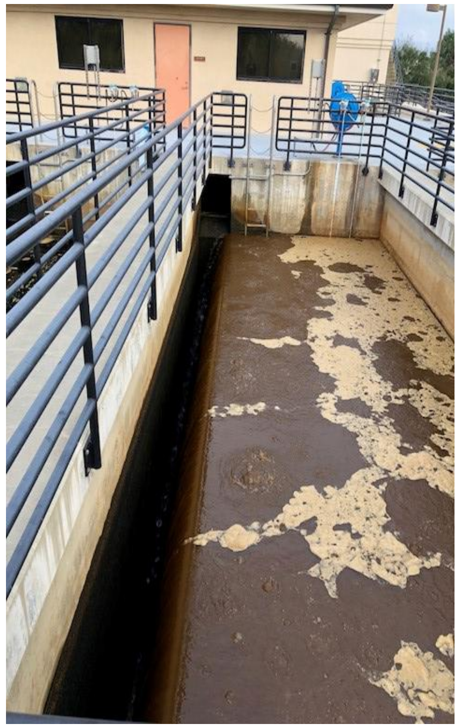


Figure 6.9: Filter Backwash Collection Basins[32]

The filter is in the process of a filter back wash. The water is moving in the opposite direction and overflowing over the weir and heads to the waste basin where it is collected and eventually returned into the head works of the plant to be treated again.

As a water treatment operator you will be expected to have knowledge of how to properly use equipment related to filtration. While running a treatment plant you will routinely:

- monitor filter performance
- check turbidity levels with online analyzers and grab samples
- adjust chemical flow rates
- backwash filters
- visually inspect filters

Filters run differently under changing water conditions. The plant will not always run the same as temperature differences and storm events will make operators examine important operational considerations from time to time. It is important to look at the weather and understand how it might affect the treatment plant. A severe rainstorm near your source water could increase turbidity levels coming into the plant. Under these conditions, operators may have to wash filters more frequently and adjust chemical doses.

[32] Photo provided by author.

There are other abnormal conditions to consider when monitoring filter performance. Monitor filter washes to look for mud balls, excessive boiling in certain spots, and media being displaced and sent to waste basins. These conditions would indicate that the backwash flow is too high. Also identify shorter filter run times, filters that may not be coming clean, and algae growth. These factors may be due to improper chemical dosing and a back wash flow that is too low.

FILTRATION MATH

Filtration Rate

Calculating the filtration rate of the filters in your plant is an important task. Operating plans and permits limit the amount of water a filter can produce so it is important to understand filter rates (also known as loading rates). Filtration rates will also give an operator a basic understanding of the treatment plants daily average production.

The filtration rate formula is a velocity equation. These formulas are easily confused with flow problems so make sure you pay attention to the units you add into the formula and pay attention to what the problem is asking. The formula for filtration rate is:

$$\text{Filtration Rate} = \frac{\text{Flow}}{\text{Surface Area}}$$

Filtration rate equations will use GPM and the area of a given filter. The area of the filter is length multiplied by width. A problem may give you the depth of a filter to confuse you. Pay very close attention to the wording in the problem.

Example: What is the filtration rate of a treatment plant that has 3 filters that are 20 ft wide and 20 ft in length in a plant that produces 1 MGD?

Step 1: Determine the total surface area of the filters.

$$\text{Area} = 20\text{ ft} \times 20\text{ ft} = 400\text{ ft}^2$$

Since there are a total of 3 filters, the total area is:

$$\text{Area} = 400\text{ ft}^2 \times 3 = 1{,}200\text{ ft}^2$$

Step 2: Convert the flow rate from MGD to gpm.

$$\frac{1\text{ MG}}{\text{day}} \times \frac{1\text{ day}}{24\text{ hrs}} \times \frac{1\text{ hr}}{60\text{ min}} \times \frac{1{,}000{,}000\text{ gal}}{1\text{ MG}} = \frac{694.44\text{ gal}}{\text{min}}$$

Step 2: Calculate the Filtration Rate.

$$\text{Filtration Rate} = \frac{\text{Flow}}{\text{Surface Area}}$$

$$\text{Filtration Rate} = \frac{694 \text{ gpm}}{1{,}200 \text{ ft}^2} = 0.578333 \text{ gpm/ft}^2$$

BACKWASH RATE

As discussed in the chapter, after a filter reaches its capacity due to head loss, turbidity break through, or maximum number of hours run, the filter must be washed. The filter wash cycle water velocity will be much greater than the amount of water that flows through the filter during normal operation. The backwash is the flow of water in the opposite direction where water is moving up instead of down.

Although filtration rates are commonly expressed as gpm/ft^2, they are also expressed as the distance of fall (in inches) within the filter per unit of time (in minutes). This "fall" references the fact that filtration rates are reduced over time as particles are lodged into the filtration media during operation. Backwashing, a process of cleaning the media by reversing the flow through the filter, is then employed in order to try and recover some of the filtering capacity and prolong the operational life of the filter. During backwashing, the formula is expressed with the same units as "fall" but is described as "rise" in the filter instead. This lets you know how much filtering capacity is recovered through your backwashing cycle. Operators may be asked to solve for this rate of "rise" which is expressed as in/min. Use the formulas below.

$$\text{Filtration Rate} = \frac{\text{Fall (inches)}}{\text{Time (min)}}$$

$$\text{Backwash Rate} = \frac{\text{Rise (inches)}}{\text{Time (min)}}$$

The conversion from gallons per minute per square foot to inches per min requires converting gallons to cubic feet, then feet to inches.

Example: Express 2.5 gpm/ft^2 as in/min.

First, convert gpm to cfm. This is the first step toward converting the gallons to inches.

$$\frac{2.5 \text{ gpm}}{\text{ft}^2} \times \frac{1 \text{ ft}^3}{7.48 \text{ gal}} = \frac{0.33 \text{ cfm}}{\text{ft}^2}$$

In the above conversion, the gallons canceled, and you were left with cubic feet per min divided by square feet. This can cancel further.

$$\frac{0.33\ ft^3/m}{ft^2} = 0.33\ ft/min = \frac{0.33\ ft}{min}$$

When you divide cubic feet by square feet, you are left with feet. The result in this example is feet per minute.

Feet per minute can easily be converted to inches per minute by multiplying by the conversion 12 inches equals 1 foot.

$$\frac{0.33\ ft}{min} \times \frac{12\ in}{1\ ft} = \frac{4\ in}{min}$$

However, this can be simplified by using the following unit conversion.

$$\frac{1.6\ in}{min} = \frac{1\ gpm}{sqft}$$

$$\frac{1.6\ in/min}{1\ gpm/sqft} \quad \text{or} \quad \frac{1\ gpm/sqft}{1.6\ in/min}$$

Example: Express 2.5 gpm/ft^2 as in/min.

Use the unit conversion to solve this problem.

$$2.5\ gpm/ft^2 \times \frac{1.6\ in/min}{1\ gpm/sqft} = 4\ in/min$$

Example: What is the filtration rate through a 20’ by 20’ filter if the average flow through the treatment process is 2.5 MG? Express the filtration rate as in/min.

First, convert 2.5 MGD to gpm. To do this divide 2.5 MGD by 1,440.

$$\frac{2{,}500{,}000\ gal}{day} \times \frac{1\ day}{1{,}440\ min} = 1{,}736\ gpm$$

Next, calculate the surface area of the filter in square feet.

$$20\ ft \times 20\ ft = 400\ ft^2$$

To calculate the filtration rate, substitute the values into the formula.

$$\text{Filtration Rate (gpm/ft}^2\text{)} = \frac{\text{Flow (gpm)}}{\text{Surface Area (ft}^2\text{)}}$$

$$\text{Filtration Rate (gpm/ft}^2\text{)} = \frac{1{,}736 \text{ gpm}}{400 \text{ ft}^2} = 4.32 \text{ gpm/ft}^2$$

Now use the unit conversion to calculate the filtration rate as inches per minute.

$$\text{Filtration Rate} = 4.32 \text{ gpm/ft}^2 \times \frac{1.6 \text{ in/min}}{1 \text{ gpm/sqft}} = 6.912 \text{ in/min}$$

Example: The maximum back wash rate for a filter is 5,000 GPM. The filter is 20 feet wide and 20 feet in length. What is the rate of rise in the filter?

Step 1: Determine the surface area of the filter.

$$\text{Area} = 20 \text{ ft} \times 20 \text{ ft} = 400 \text{ ft}^2$$

Step 2: Calculate the Backwash Rate.

$$\text{Backwash Rate} = \frac{\text{Flow}}{\text{Surface Area}}$$

$$\text{Backwash Rate} = \frac{5{,}000 \text{ gpm}}{400 \text{ ft}^2} = 12.5 \text{ gpm/ft}^2$$

Step 3: Convert the Backwash Rate to inches per minute.

$$12.5 \text{ gpm/ft}^2 \times \frac{1.6 \text{ in/min}}{1 \text{ gpm/sqft}} = 20 \text{ in/min}$$

Percent Backwash

Water treatment plants are very efficient at recycling waste stream water. The water sent to waste basins and lagoons can be recycled, but only a certain amount at a time. The percent backwash math problems compare the total plant production with the amount of finished water used to backwash a filter.

Example: A treatment plant treats 2 MGD. It has 2 filters that are washed each day and each use 10,000 gallons during the wash. What is the percent of backwash water?

Step 1: Determine the total amount of water used each day to wash the filters.

$$2 \text{ filters} \times \frac{10{,}000 \text{ gallons}}{\text{filter}} = 20{,}000 \text{ gallons}$$

Step 2: Calculate what percentage 20,000 gallons is of the total plant treated water flow of 2 MGD.

$$20{,}000 \text{ gallons} = x\% \text{ of } 2{,}000{,}000 \text{ gallons per day}$$

$$x\% = \frac{20{,}000 \text{ gallons}}{2{,}000{,}000 \text{ gallons per day}} \times 100 = 0.01 \times 100 = 1\% \text{ per day}$$

The treatment plant uses 1% of the water per day for backwash.

Key Terms

- **backwash procedure** – the reverse flow of water through the filter in the water treatment
- **conventional treatment** – water treatment that includes sedimentation process as part of treatment
- **diatomaceous earth treatment** – accomplished through pressure filtration; also, can also be referred to as precoat filtration; in this method, the filter media in this case is added as slurry to the treatment vessel. Within the vessel lays a pipe known as a septum. The slurry attaches itself to the septum and water is run through the vessel where pathogenic and suspended material is captured and strained out of the finished water; very common for swimming pool treatment and beverage companies but not practical for larger municipalities because of the large amount of disposal of sludge and the continuous purchasing of filter media
- **direct filtration** – differs from conventional treatment because the sedimentation process is skipped; areas with source water higher in quality may opt for direct filtration to reduce costs and the amount of land space for sedimentation basins can be substantial
- **filtration** – the final and most important removal requirement required by the Surface Water Treatment Rule (SWTR) in which water passes through material such as sand, gravel, and anthracite coal to remove floc and disease-causing microorganisms from the finished water
- **schmutzdecke** – a chemical layer that is part of slow sand filtration facilities
- **slow sand filtration** – a less common method of filtration due to the large amount of time it takes to treat water and the amount of space the facilities require

CHAPTER REVIEW

1. How are solids removed from a filter?
    a. adsorption
    b. straining
    c. deactivation
    d. flocculation

2. What is a typical filtration rate for slow sand filters?
    a. 2.0-6.0 GPM/sq. ft
    b. 6.0-10.0 GPM/sq. ft
    c. 1.0-2.0 GPM/sq. ft
    d. 0.5-0.10 GPM/sq. ft

3. In a typical conventional treatment plant, the finished water turbidity for an individual filter should be less than how many NTUS?
    a. 1.0 NTUs
    b. 0.3 NTUs
    c. 5.0 NTUs
    d. 3.0 NTUs

4. How will head loss be affected by a filter running under normal conditions?
    a. remain constant
    b. increase slowly
    c. rapidly increase
    d. decrease slowly

5. Under what conditions must a filter be washed?
    a. head Loss
    b. turbidity break through
    c. maximum filter run time
    d. all of the Above

6. How is filter performance measured?
    a. oxygen
    b. head loss
    c. turbidity
    d. chlorine

7. What is the biologically active layer of a slow sand filter called?
    a. mixed Media
    b. dual Media
    c. sludge Layer
    d. schmutzdecke

8. What is the pressure drop in a filter called?
    a. turbidity breakthrough
    b. head loss
    c. filtration
    d. backwash

9. What is the most common reason for putting a filter into the wash cycle?
    a. head loss
    b. filter run time
    c. turbidity breakthrough
    d. water level decrease

10. What causes formation of mud balls and excessive boiling during a wash?
    a. proper backwash rate
    b. too low backwash rate
    c. excessive backwash rate
    d. improper chemical dose

11. What are important processes during filtration?
    a. sedimentation
    b. adsorption
    c. straining
    d. all of the Above

12. What are typical filtration rates for a conventional treatment plant?
    a. 0.2-0.6 GPM/sq. ft
    b. 2.0-10.0 GPM/sq. ft
    c. 10.0-20.0 GPM/sq. ft
    d. 200-400 GPM/sq. ft

13. There are four filters at a water treatment plant. The filters measure 20 feet wide by 30 feet in length. What is the filtration rate if the plant processes 8.0 MGD?
    a. 1.51 GPM/sq. ft
    b. 2.31 GPM/sq. ft
    c. 2.61 GPM/sq. ft
    d. 2.91 GPM/sq. ft

14. A water treatment plant treats 6.0 MGD with four filters. The filters use 60,000 gallons per wash. What is the percent backwash at the plant?
    a. 10 %
    b. 8 %
    c. 6%
    d. 4%

15. A treatment plant filter washes at a rate of 10,000 GPM. The filter measures 18 feet wide by 24 feet long. What is the rate of rise expressed in inches per minute?
    a. 17 inch/min
    b. 27 inch/min
    c. 37 inch/min
    d. 47 inch/min

CHAPTER 7 – DISINFECTION

The final step in the water treatment process before finished or treated water enters a clear well for storage is the disinfection process. **Disinfection** is the process where chemical agents are added to a water source to kill or inactivate pathogenic microorganisms. Pathogenic microorganisms are disease causing and must be eliminated from treated water.

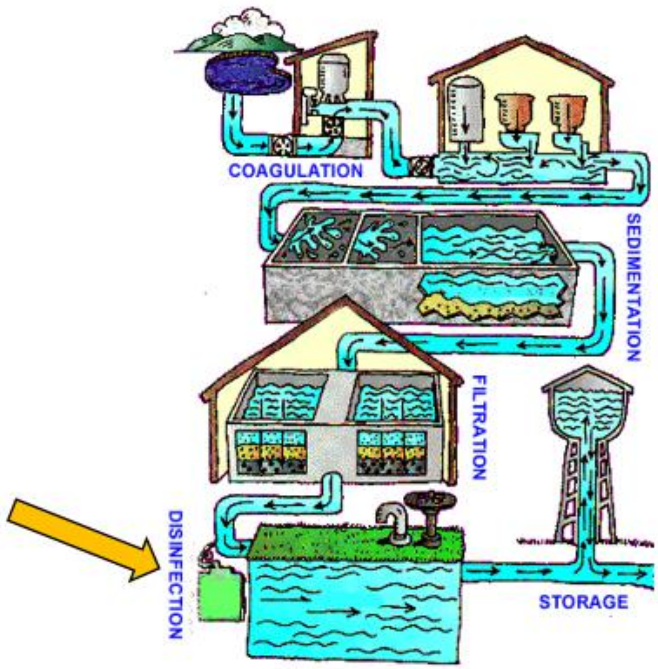


Figure 7.1: The Water Treatment Process[33]

After reading this chapter, you should be able to:

- apply disinfection terminology;
- understand water treatment regulations; and
- identify types of disinfectants used during water treatment.

DISINFECTION BASICS

Treatment plant operators use the two-part process of removal and deactivation of microbiological constituents in water. Most of the pathogens water treatment professionals remove and deactivate from drinking water have adapted to living in the bodies of warm-blooded animals. Pathogens thrive and survive in those environments. Outside those environments, these pathogens can stay dormant until they are consumed. Even more frightening, some of the illnesses can cause death.

[33] Image of water treatment by the EPA is in the public domain

Because of limitations in testing, it is difficult to indicate the presence of specific waterborne illnesses caused by virus, bacteria, and *Giardia*. Water professionals use tests such as the total coliform test to look for the likely presence of waterborne disease. The Surface Water Treatment Rule sets specific guidelines for removal and treatment to ensure the removal and inactivation of pathogenic organisms.

Strict regulations set forth by the Safe Drinking Water Act were created to ensure the public's drinking water was safe to consume. To ensure drinking water is safe for human consumption, 3 log removal and deactivation or 99.9% of *Giardia* lamblia is required. For viruses, 4 log or 99.99% removal and deactivation is required. Bacteria fall in the middle of viruses and *Giardia,* so the government determined it was not necessary to have regulations specifically regulating their inactivation and removal.

Below is a list of waterborne diseases and illnesses.

Table 7.1 - Waterborne Diseases and Illnesses

Bacteria	Internal Parasite from Protozoa	Virus-caused
• Anthrax • Dysentery • Cholera • Gastroenteritis (Stomach Flu) • Leptospirosis • Paratyphoid • Salmonella • Shigellosis (Shigella) • Typhoid fever	• Dysentery • Ascariasis (round worm) • Cryptosporidiosis from *Cryptosporidium* • Giardiasis from *Giardia*	• Gastroenteritis • Heart anomalies • Hepatitis A • Meningitis • Poliomyelitis

PURPOSE OF DISINFECTION

Operators disinfect water to destroy the harmful organisms listed in the above chart. Filtration is used to remove the organisms while disinfection kills them or deactivates them. Operators do not sterilize water because sterilization would kill everything in the water. The process of disinfection relies heavily on everything that occurs downstream in the treatment process. As water enters the treatment plant in the form of raw water, the chemistry of that water affects how well the specific disinfectant will work at each stage of the treatment process.

WHAT AFFECTS DISINFECTION?

There are several characteristics of water that can affect treatment. Water is more easily disinfected with higher temperatures. In lower temperatures, longer contact times may be required and larger amounts of chemical must be used. Higher turbidity rates will decrease disinfection as well. Excess turbidity will require greater amounts of chemical to properly disinfect the water supply. Chemicals such as chlorine can interact with organic and inorganic matter. Chlorine's ability to interact with these constituents may reduce or eliminate the effectiveness of the disinfectants.

TYPES OF DISINFECTANTS PHYSICAL

Physical disinfection is not widely used to treat potable water at this time. Ultraviolet rays are starting to be used more consistently, but chemical means of disinfection must still be used as ultraviolet (UV) disinfection does not carry a disinfectant residual. The UV process is very expensive and thus is not used by large scale treatment operations in the United States. Other means of physical disinfection include boiling and ultrasonic wave production. Agencies will call for boil water notifications during emergencies and when there is a waterborne illness outbreak, but it is not used as a primary means to disinfect drinking water.

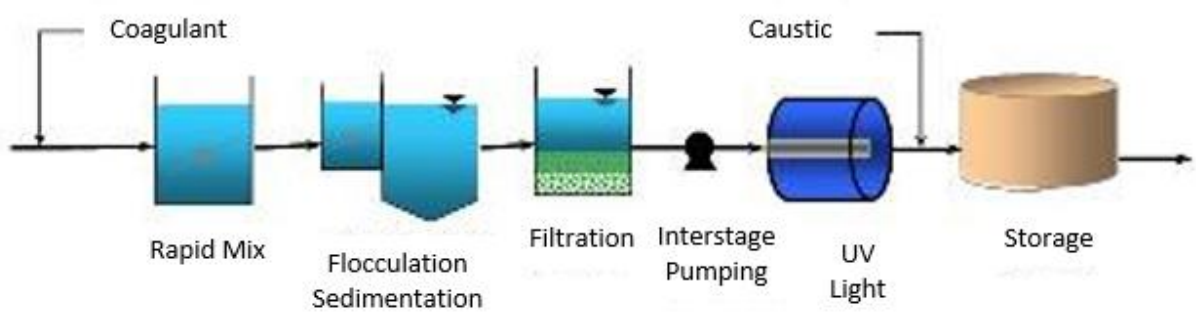


Figure 7.2: Ultraviolet Disinfection[34]

TYPES OF DISINFECTANTS CHEMICAL

There are several chemical disinfectants available in drinking water applications. The most used in the United States is chlorine. The topic of chlorine will be discussed in greater detail in the following chapter. The basics will be covered below as well as a background on the other chemicals available. The chemicals will be broken down into sub-categories based on their practical usage in the United States.

[34] Image by the EPA is in the public domain

Rare Disinfectants

- Iodine - It is commonly used for emergency treatment in the form of droplets or tablets. It is not used by the water treatment industry because of its cost and the potential health hazards to pregnant women and possible thyroid issues, which can develop with frequent use. EPA facts about Iodine - https://semspub.epa.gov/work/HQ/176317.pdf
- Bromine - It is not used by water treatment facilities as it is very corrosive and can cause severe skin burns. It is used more commonly as a disinfectant in swimming pools. When it reacts with choline (a common nutrient from plants and animals) in water, it can create disinfectant by-products. It was used by the United States Navy for a time, but most systems have been removed because of bromine's corrosiveness.
- Sodium Hydroxide and Lime - more frequently used to sterilize pipes. They are not used as an everyday disinfectant because of the bitter taste that is left behind after application. Sodium hydroxide and lime are more often used to increase the pH of the water in the distribution system after treatment with gas chlorine.

More Common Disinfectants

- Chlorine Dioxide - used as a water treatment disinfectant and oxidizer. It does not react with ammonia which is an issue with chlorine. Chlorine dioxide is used as a disinfectant but is also very effective at removing iron, manganese, taste, odor, and color from treated water. *Cryptosporidium* is resistant to chlorine, but is not resistant to chlorine dioxide. Up to 70 percent of chlorine dioxide is converted to chlorite, which is a regulated disinfectant by-product so the dosage rates when using it as a disinfectant must be lower than 1.4 mg/L. Chlorine dioxide must also be made on site which necessitates higher operational and maintenance costs.
- Ozone - Ozone was first used in Europe in the early 1900's. It is a strong disinfectant that also reduces taste and odor issues. The drawback of ozone is that it is very expensive to produce, has high electrical costs, has limited solubility, and does not leave a residual in the treated water because it is so reactive. If bromide is present in the water, ozone can react with it to form bromate, an undesirable DBP. Ozone is very efficient at disinfecting *Cryptosporidium,* so it is generally used as a secondary disinfectant along with chlorine or chloramines.

Most Common

- Chlorine - The most widely used disinfectant in the United States is free chlorine. Chlorine can be added as a gas in the form of chlorine gas, as a solid in the form of calcium hypochlorite, or as a liquid in the form of sodium hypochlorite. Most likely, you have a bottle of sodium hypochlorite in your house. We call it bleach. The use of free available chlorine has declined over the years because of the discovery of disinfectant by products. This topic will be discussed in further detail in the next chapter.
- Chloramines - The use of chloramines has become more common in recent years to reduce DBPs, mainly trihalomethane (THM). Chloramines are also referred to as

combined chlorine as it is the combination of chlorine and ammonia. Chloramines are also effective at eliminating taste and odor problems and the residual lasts longer in the distribution system. However, chloramine disinfection is not as strong as chlorine and the improper addition of ammonia can lead to excessive amounts of ammonia in the treated water which results in nitrification.

7.3 Ozone Generators[35]

REGULATIONS

The **Safe Drinking Water Act (SDWA)** is the basis of all drinking water regulations in the United States. It is the umbrella in which all new regulations and rules have subsequently been created and enacted. The SDWA regulates drinking water standards in the United States along with its territories. We take for granted all the research and technology we have available that allows us to never really be concerned about the quality of our drinking water. The SDWA was passed in 1974 and set fourth standards to regulate public water sources. It was amended in 1986 to include some basic principle definitions:

- defined regulated contaminants and approved treatment techniques
- defined criteria for filtration of drinking water
- defined criteria for disinfecting surface and groundwater
- outlawed the use of lead material in drinking water facilities.

After a large public health crisis in Milwaukee, Wisconsin, provisions were made to support drinking water programs through operator training and certification programs. All entities serving water to the public were required to meet program standards with regards to training and certification. In 1999 the government allowed states to hold primacy over drinking water

[35] Image by olegschedrin0 is licensed under CC0

certification programs if federal minimums were met. States such as California often have stricter standards than the federal standards.

Surface Water Treatment Rule

The Surface Water Treatment Rule (SWTR) was enacted in 1990 and sought to prevent waterborne illness from surface water sources. Water systems with supplies from surface sources which are susceptible to carrying viruses, legionella, and *Giardia lamblia*, must follow new requirements with regards to filtration and disinfection known as the multiple barrier approach. The rule also required that systems that used groundwater as a source for drinking water had to adhere to SWTR standards if their water source could meet surface water sources.

Water treatment plants would have to achieve removal and deactivation requirements through the combined efforts of filtration and disinfection. The removal and deactivation of 99.9% of *Giardia* or 3 Logs and the removal and deactivation of 99.99% of viruses or 4 Logs was the new standard set forth. This requirement is measured by monitoring combined effluent turbidities in the combined filters and meeting disinfection requirements through the CT calculation. The CT calculation will be covered in greater detail in the following chapter.

Groundwater Rule

The Groundwater Rule (GWR) was established in 2009 in response to the frequency of groundwater contamination from surface water runoff sources. The rule requires monitoring for systems that do not disinfect to make sure microbiological contamination is not occurring. If a groundwater supplier did use disinfection, they are to meet 99.99% virus inactivation much like groundwater sources.

Total Coliform Rule

The final rule which indirectly relates to water disinfection is the **Total Coliform Rule (TCR)** which was established in 1990. As stated, several times within the text, it is nearly impossible and certainly too costly to test for every type of microbiological contaminant that could lead to a public health risk. Instead, the TCR uses a risk based process which tests for the “worst case scenario”. Coliforms grow in warm blooded animals just like viruses, bacteria, and *Cryptosporidium*. They pose no health risk to humans and they grow more abundantly than forms of microbiological agents that will do us harm. If coliforms are present in the water supply, there is a chance for a public health concern.

In the event of a positive coliform test, the downstream and upstream sampling sites as well as the site where the positive sampling occurred will be retested. System maps and sampling plans are a requirement of the TCR. The number of samples the water supplier takes is based on the population served. Systems which collect less than 40 samples a month can only have one positive sample before notifying the public of a Maximum Contaminant Level (MCL) violation. Systems that collect more than 40 samples a month must not have positives in more than 5% of their coliform samples. If you work at a water supplier which takes 50 samples a month and had 3 positive samples are you in compliance with the TCR?

47 ÷ 50 = .94 .94 × 100 = 94% (6% of the samples were positive so you would not be in compliance.)

Or

3/50 = 0.06 0.06 × 100 = 6% Therefore, 3 positives are 6% of the total samples.

Disinfectant By-Product Rule

The **disinfectant by-product rule (DBPR)** was put in place to protect the public from cancer causing risks associated with disinfectants reacting with organic and inorganic matter in treated drinking water. Disinfectant by-products such as trihalomethanes are classified as volatile organic compounds. The Stage 1 DBPR established maximum contaminant levels for several DBPs including:

- Trihalomethane (TTHMs) - 80 ug/L or 80 ppb
- Haloacetic Acid (HAA5) - 60 ug/L or 60 ppb
- Bromate - 10 ug/L or 10 ppb
- Chlorite - 1.0 ppm

While it is all together possible to remove DBPs from treated water with activated carbon, it is a very expensive treatment process and not cost effective for large treatment operations. Other forms of disinfection are possible but will also cause DBP formation. Chlorite formation is associated with chlorine dioxide treatment, while bromate is associated with ozone treatment. The issue of DBP formation becomes even more problematic as chlorite and bromate are often found naturally in source water.

The stage II DBP Rule enhanced regulations on DBP formation by targeting water sources that are more vulnerable to DBP formation and the rule also requires monitoring for HAA5s and THMs. The number of samples taken, and the number of sampling sites is based on the size of the population served by the water agency. The use of chloraminated water is being used more commonly to combat DBP formation, but using chloramines instead of other disinfectants has other risks associated with its use which will be covered in greater detail in the next chapter. This is the link to the quick reference guide from the EPA with information on the Stage I and Stage II DBP rule.

Key Terms

- **disinfection** – the process where chemical agents are added to water to kill or inactivate pathogenic microorganisms
- **disinfection by-product rule** –to protect the public from cancer causing risks associated with disinfectants reacting with organic and inorganic matter in treated drinking water
- **Safe Drinking Water Act (SDWA)** – the basis of all drinking water regulations in the United States as the umbrella in which all new regulations and rules have subsequently been created and enacted
- **Total Coliform Rule (TCR)** – was established in 1990 to use a risk based process which tests for the "worst case scenario"

CHAPTER REVIEW

1. What is residual chlorine?
    a. chlorine used to disinfect
    b. the amount of chlorine after the demand has been satisfied
    c. the amount of chlorine added before disinfection
    d. film left on DPD kit to measure residual

2. When chlorine reacts with natural organic matter, what does it create?
    a. disinfectant by-products
    b. coliform bacteria
    c. chloroform
    d. calcium

3. What are trihalomethanes classified as?
    a. salts
    b. inorganic compounds
    c. volatile organic compounds
    d. radio

4. What disinfectant is used for emergency purposes and not utilized in the water treatment industry?
    a. chlorine
    b. iodine
    c. ozone
    d. chlorine dioxide

5. What is the disinfectant with the least killing power but that has the longest lasting residual?
    a. chlorine
    b. ozone
    c. chlorine dioxide
    d. chloramines

6. What is the active ingredient in household bleach?
    a. calcium hypochlorite
    b. calcium hydroxide
    c. sodium hypochlorite
    d. sodium hydroxide

7. What is *Cryptosporidium* not resistant to?
    a. ozone
    b. chlorine dioxide
    c. chlorine
    d. Both A & B
    e.
8. The removal and inactivation requirement for *Giardia* is?
    a. 99.9 %
    b. 99.99 %
    c. 99.00 %
    d. 90%

9. If a coliform test is positive, how many repeat samples are required at a minimum?
    a. None
    b. 1
    c. 3
    d. Depends on the severity of the positive sample

10. Your water system takes 75 coliform tests per month. This month there were 6 positive samples. What is the percentage of samples which tested positive? Did your system violate regulations?
    a. 3% Yes
    b. 5 % No
    c. 8 % Yes
    d. 10 % No

CHAPTER 8 – CHLORINE

Chlorine is the chemical most frequently used in the water treatment industry for disinfection to meet the standards of the surface water treatment rule. Chlorine is used in several different forms and can be fed into the system in a variety of different methods. It is a very dangerous chemical, so proper safety and handling procedures must always be followed. In addition to being used as a disinfectant, chlorine may also be used as controlling agent for the removal of algae, for taste, and for odor. Other beneficial applications of chlorine include disinfection of new water facility infrastructure such as pipes and tanks and the oxidation of iron, manganese, and hydrogen sulfide. After reading this chapter, you should be able to:

- use and apply chlorine terminology;
- explain chlorine chemistry;
- summarize chlorine safety; and
- complete advanced chlorine calculations.

CHLORINE TERMINOLOGY

Chlorine is available in three forms, which are shown below:

1. Gaseous (chlorine)- Cl_2
2. Solid (calcium hypochlorite)- $Ca(OCl)_2$
3. Liquid (sodium Hypochlorite)- NaOCl

Adding chlorine to a water supply causes chemical reactions to take place between the water and the organic and inorganic molecules within the water. After chlorine is done combing with organic and inorganic material in the water, the demand has been satisfied. It is not explicitly known how chlorine disinfection works. One explanation is that chlorine attacks a bacterial cell and destroys it. The other theory suggests that chlorine deactivates enzymes within the cell enabling the microorganisms to use their food supply.

The dose of chlorine minus the demand is the **residual**. The reason chlorine is used in the United States over other disinfecting chemicals is chlorine’s ability to leave a lasting residual within the framework of the water distribution system. This residual continues to fight potential disease causing microorganisms after treatment has concluded.

Assume that you are working as an operator at a water treatment plant. Your chief operator would like to maintain a residual of 2.0 mg/L of chlorine residual in the distribution system. The demand is 1.5 mg/L. What is the dose you must add to achieve a residual of 2.0 mg/L?

$$\text{Dose} = \text{Demand} + \text{Residual}$$

$$\text{Dose} = 2.0\ \text{mg/L} + 1.5\ \text{mg/L} = 3.5\ \text{mg/L}$$

Therefore, you would need to maintain an average of a 3.5 mg/L dose of Chlorine to achieve the residual requested by your chief operator.

Other chlorine terminology includes free chlorine, combined chlorine, and total chlorine. It is important to understand these terms before taking a deeper dive into the chemistry of chloramination. The term **free or available chlorine** refers to the amount of chlorine that is “free” or “available” in the system to kill or deactivate pathogenic organisms. **Combined chlorine** is chlorine that has combined with other molecules and **total chlorin**e is the combination of free or available chlorine and combined chlorine. Although combined chlorine lasts longer in the distribution system, it is a far less effective disinfectant. It is also important to note, not all chlorine has the same strength.

CHLORINE CONTENT

As mentioned earlier in the chapter, chlorine is available in different states of matter. The amount of chlorine used to dose water in a treatment plant is determined by the compound used. Below is a chart illustrating the different compounds of chlorine. The percent column indicates the percentage of chlorine in the compound. For example, chlorine gas is pure chlorine and yields the highest available percentage at 100%.

Table 8.1 - Chlorine Content in Different Chlorine Compounds

Chlorine Compound	Percent	Amount needed to attain 1lb
Chlorine Gas	100	1 lbs
Calcium Hypochlorite	65	1.54 lbs
Sodium Hypochlorite	15	.8 gallons
Sodium Hypochlorite	12.5 (most common)	1.0 gallons
Sodium Hypochlorite	5 (household bleach)	2.4 gallons

In the math section of this chapter, the impact of the chlorine percentage will become evident. It is important to read the question and understand what concentration of chlorine is being added to the treatment plant. The third column in the table, provides the pound or gallon needed of the specific compound to provide 1 pound of chlorine. For example, if your plant requires a weight or quantity of 100 lbs of chlorine and you use gas chlorine, then you will be adding 100 lbs. of chlorine gas. If you are using calcium hypochlorite, you will need to calculate the number of pounds required. From the table, calcium hypochlorite is 65% chlorine. To determine the total number of pounds of calcium hypochlorite needed to provide 1 pound of chlorine, divide the dose required by the percent chlorine.

$$100 \div 0.65 = 153.8 \text{ lbs}$$

Therefore, you will need to use 153.8 lbs of calcium hypochlorite to obtain a 100 lbs dose of chlorine.

FACTORS OF CHLORINE SUCCESS

Several factors during the water treatment process will impact the effectiveness of the Chlorine. The five factors that affect chlorine treatment are:

- The concentration of chlorine, more specifically the dose
- The amount of time chlorine is in contact with the water
- The temperature of the source water
- The pH of the source water
- The constituents in the source water

The amount of time the chlorine is in contact with the water determines the effectiveness of the chlorine disinfection. The CT (Concentration multiplied by Contact Time) formula is used to calculate the time chlorine is in contact with the water. C is the concentration of chlorine residual, so CT is expressed as (mg/L-min). If water is leaving a drinking water storage tank, also referred to as a clear well, at a rapid rate, then the chlorine concentration will have to be increased. If the concentration of chlorine is decreased, then the water will have to stay in contact with the disinfectant for a longer period. Combined chlorine treatment associated with monochloramine disinfection will require longer holding periods due to its decreased effectiveness.

Temperature affects chlorine treatment in a variety of ways. Chlorine is more effective at killing pathogens at higher temperatures, but at lower temperatures, the chlorine residual will last longer. Practically speaking, chlorine disinfection works better in warmer temperatures as more credit is given with the CT calculation. The pH level of the water is also a significant factor when treating with chlorine. The ratio of HOCl to OCl^- is affected based on the pH. HOCl will remain the dominant disinfectant in water with a lower pH while OCl^- will remain in higher quantities in water with a higher pH.

In the disinfection process, chlorine not only reacts with organisms that are to be killed, but it also reacts with the turbidity in the water and other substances such as ammonia. Reducing turbidity in treated water through coagulation, sedimentation, and filtration ensures disinfection will be more effective. The maximum and minimum chlorine residual in the distribution system is 4.0 mg/L and 0.2 mg/L respectively. However, corrective measures must be taken when you see the residual in the distribution system dramatically decreasing. You would never want to see the minimum chlorine residual of 0.2 in the distribution system.

CHLORINE CHEMISTRY

Below is the reaction that occurs between water and free available chlorine:

Cl_2 (chlorine) + H_2O (water) $\rightarrow$ HOCl (hypochlorous acid) + HCL (hydrochloric acid)

Hypochlorous acid is more effective of the two forms of available chlorine. First, it is important to understand how chlorine demand works. We can do this by examining the effects of adding free available chlorine to distilled water. If we were to dose distilled water with 1.0 mg/L of free available chlorine, the residual would be 1.0 mg/L chlorine because there is nothing in distilled water that will react with the chlorine other than the water itself. Distilled water lacks impurities.

Raw source water is filled with impurities. Chlorine will have many constituents to react with during the treatment process. When the chlorine reacts with the water and the impurities, five different types of chlorine residuals result. The following chart illustrates the effectiveness of each type of residual. The most effective is hypochlorous acid (HOCl) so the effectiveness of the remaining four types of residuals are in comparison to HOCl.

Table 8.2 - Effectiveness of Different Residuals

Residual	Abbreviation	Effectiveness
Hypochlorous Acid	$HOCl$	1
Hypochlorite Ion	OCl^-	1%
Trichloramine	NCl_3	More info later in chapter
Dichloramine	$NHCl_2$	1.25 %
Monochloramine	NH_2Cl	.667%

As the chart shows, dichloramines are a "more effective" disinfectant than monochloramines but their use may cause taste and odor problems. The effectiveness of trichloramines has not been extensively researched and as with dichloramines, a pungent taste and odor problem occurs with its use. Thus, the water industry only uses monochloramines as a disinfectant. Below are the chemical formulas which illustrate when hypochlorous acid disassociates and becomes a weaker disinfectant.

HOCl (hypochlorous acid) $\longrightarrow$ H^+ (hydrogen ion) + OCl^- (hypochlorite ion)

HCl (hypochloric acid) $\longrightarrow$ H^+ (hydrogen ion) + Cl^- (chlorine ion)

CHLORINE HANDLING AND SAFETY

As a treatment operator you will encounter many dangerous chemicals used to treat water. One chemical that is widely used in the water treatment industry is chlorine. As discussed earlier in the chapter chlorine comes in three different states: gas, powder, and liquid. All three types of chlorine have risks associated with the handling and storage of the chemical. It is important that proper safety procedures are always followed .

CHLORINE GAS

Chlorine gas is 2.5 times heavier than air. The odor is pungent, and the color is greenish-yellow. Gas chlorine is only visible in very high concentrations and you don't ever want to see it.

Chlorine gas is irritating to eyes, nasal passages, and the respiratory system. It is a very dangerous substance and concentrations as low as 100 parts per million can kill a person.

Chlorine gas is available in three different types of containers: 150 pound containers, 1 ton containers, and, for very large plant operations, in railroad containers. Most treatment operations will use chlorine tanks. The amount of chlorine used in a given day will determine which type of chlorine container your plant will use.

When delivered to a treatment plant, the “150 pound” chlorine gas cylinder container weighs roughly 250-280 pounds. A chlorine cylinder consists of the cylinder body, neck ring, valve, and protective hood.

Cylinders are transported around the facility with the use of a dolly or hand truck. The use of a safety chain or strap is always mandatory . Cylinders should never be rolled because it could lead to employee injury or the shearing off the valve. The maximum daily withdrawal rate for a chlorine cylinder is 40 pounds.

Chlorine “ton” containers hold 2000 pounds of chlorine and usually weigh around 3700 pounds when filled with chlorine. The containers are shipped and stored horizontally. The edge of the chlorine container has a ring, which enables cranes and hoists to move them from the truck to the storage or withdrawal area. Containers are stored on trunnions that allow operators to rotate containers with the use of a special tool. Each container has two valves, one at the top and one at the bottom. The top valve allows the chlorine to be withdrawn as a gas while the bottom valve allows chlorine to be withdrawn as a liquid. When putting containers in storage, they should place such that the liquid chlorine can settle in the bottom of the container. The maximum daily withdrawal rate for a 1-ton tank is 400 pounds.

Gas chlorine cylinders and 1-ton containers use similar methods to feed chlorine into the water. Feeding systems include a scale, valves and piping, a chlorinator, and an injector or diffuser. The weighing scales are used to keep track of how much chlorine has been used or is left in the cylinder or tank. Record keeping is critical for all chemical use. Monitoring and reviewing the recorded data can help identify problems with the chlorine system and manage costs by reducing chemical waste.

Figure 8.1: Standard chlorine scale and trunnion system[36]

Pictured above is a standard chlorine scale and trunnion system. The trunnion acts as a form of storage while also keeping an accurate measure of the amount of chemical left in the tanks. In California, the tanks must also be secured with straps due to earthquakes.

Valves and piping are just as important in the chlorine system as they are in the water system. Each chlorine tank or cylinder is equipped with valves which allow or prohibit the flow of the chlorine during the transfer and storage of the product. In an emergency the valves can also be used to quickly shutoff the flow of chlorine. Large scale systems will include piping manifolds that allow for the transfer of chlorine from multiple tanks. The associated feed system will include valves and piping to provide chlorine to different feed points in the system.

The chlorinator is the piece of equipment that feeds the chlorine directly into the system. Chlorine is dispersed evenly into the system based on a dosage set point using vacuum and pressure regulators. For safety, a vacuum must be maintained in the line. The vacuum ensures that the chlorine is always being pulled into the chlorine feed system. Most modern systems have emergency shutoff valves which prevent the flow of chlorine if a leak is detected. Chlorine systems will also include alarms, leak detectors, and repair kits.

Other safety measures are also required when working around chlorine gas. For example, when switching tanks, the operator should be wearing a self-contained breathing apparatus (SCBA). As noted earlier, a 0.1 part per million dose of chlorine gas can be immediately fatal.

HYPOCHLORINATION

Gaseous chlorine is the strongest and least expensive form of chlorine even with the required use of bases such as caustic soda to increase the pH of the finished water. However, due to

[36] Photo provided by author.

safety concerns associated with use and transportation of gaseous chlorine, hypochlorination is becoming more common in water treatment. When building or redesigning a treatment plant, an analysis of the costs and benefits of each type of chlorine will determine which type the facility will use.

The two types of hypochlorite used are calcium and sodium. Calcium hypochlorite is a whiteish-yellow dry chemical. It contains 65% available chlorine. Since it is highly reactive with organic compounds, special requirements must be used when storing it. Additionally, it is flammable if enough heat and oxygen are added. Calcium hypochlorite should always be added to water and not the opposite. Generally, calcium hypochlorite is primarily used for disinfecting new and repaired water mains and storage tanks. It is not used for the day-to-day treatment of finished water.

Sodium hypochlorite is a clear to yellowish liquid available in a variety of different concentrations. Household sodium hypochlorite, known as bleach, is available in a 5% solution. Treatment plant operations will use an industrial strength concentration of 12.5% available chlorine. Sodium hypochlorite does not have special storage requirements, but it is a strong base at 9-11 on the pH scale so it is highly corrosive. Additionally, the chemical loses its effectiveness over time in storage. Stored for a month, the chemical can lose 2% to 4% of its chlorine content. Direct exposure to sun and/or heat will further the loss of available chlorine. Therefore, it is recommended that sodium hypochlorite be stored no more than two weeks (in the event the treatment plant is offline) in a temperature-controlled room to prevent excessive strength loss.

CYLINDER TANK SAFETY AND CONNECTING

When attaching a chlorine regulator to a tank to go into service, safety precautions must be used. Any time you are dealing with gas chlorine, the operator must wear a respirator, but a SCBA is recommended. The SCBA has a 30-60 minute supply of oxygen. SCBA's operate under positive pressure, so in the event of a leak, no chlorine gas will be able to enter your mask, assuming a proper seal of the mask has been established. Along with a respirator or SCBA the operator should wear gloves and a long sleeve shirt when changing cylinders or tanks.

A new lead washer should be used every time a new tank is put into service. Inspect the lead washer for any deformities, cracks, or bends. Washers must be thrown out after one use. When the chlorine tank valve is first opened, rapidly open and close the valve. Use an ammonia solution near the valve and tubing to check for leaks.. If chlorine is present, you will see a white cloud. In the event of a white cloud, a leak is present. The operator will have to remove the regulator from the valve and use a new lead washer.

Lastly, be vigilant. Changing chlorine cylinders will become routine as it is something you will have to do often if your facility uses chlorine gas. Chlorine gas is a highly dangerous chemical that must be respected. Forgetting how dangerous it is, could lead to serious harm or death for you or your co-workers.

Key Terms

- **combined chlorine** – chlorine that has combined with other molecules
- **free chlorine** – also known as available chlorine; the amount of chlorine that is "free" or "available" in the system to kill or deactivate pathogenic organisms
- **residual** – the dose of chlorine minus the demand
- **total chlorine** – the combination of free or available chlorine and combined chlorine

CHAPTER REVIEW

1. Which form of chlorine is 100% available?
    a. sodium hypochlorite
    b. calcium hypochlorite
    c. calcium hydroxide
    d. baseous chlorine

2. What is the minimum amount of chlorine residual required in the distribution system?
    a. There is no minimum.
    b. mg/L
    c. 0.2 mg/L
    d. mg/L

3. What is the approximate pH range of sodium hypochlorite?
    a. 4-5
    b. 6-7
    c. 9-11
    d. 12-14

4. What is the typical concentration of sodium hypochlorite utilized by water treatment professionals?
    a. 5%
    b. 65%
    c. 100%
    d. 12.5%

5. What is chlorine demand?
    a. chlorine in the system for a given time
    b. the difference between chlorine applied and chlorine residual—usually caused by inorganics, organics, bacteria, algae, ammonia, etc.
    c. chlorine needed to produce a higher pH
    d. none of the above

6. What is the most effective chlorine disinfectant?
    a. dichloramine
    b. trichloramine
    c. hypochlorite Ion
    d. hypochlorous acid

7. What can form when chlorine reacts with natural organic matter in source water?
    a. disinfectant by-products
    b. sulfur
    c. algae
    d. coliform bacteria

8. What is the maximum withdrawal rate per day for a 150-pound chlorine cylinder?
    a. There is no maximum.
    b. 20 pounds
    c. 40 pounds
    d. 50 pounds

9. What kind of solution is used to check for a gas chlorine leak?
    a. sodium hydroxide
    b. ozone
    c. ammonia
    d. calcium hypochlorite

10. Which describes chlorine?
    a. heavier than air
    b. lighter than air
    c. brown in color
    d. not harmful to your health

11. What causes chlorine demand to vary?
    a. chlorine demand always stays the same
    b. temperature
    c. pH
    d. Both B and C

12. What effect does high turbidity have on disinfection?
    a. It can increase chlorine demand .
    b. It has no effect.
    c. It gives the water a milky appearance that will clear out after some time.
    d. You must increase the temperature of the water.

CHAPTER 9 – CHLORAMINATION AND NITRIFICATION

We may take for granted the fact that clean drinking water will flow when we turn on the tap. The water treatment profession is constantly evolving. Advancements in science and lab procedures help water professionals find constituents in drinking water that can be harmful to human beings.

Currently chlorine is the best disinfectant available. However, the use of chlorine causes any number of Disinfectant By-Products (DBPs). Many of the DBPs have not been researched and are not regularly monitored. As screening methods improve, it is likely that more of the possible DBPs will be regulated in the future. Trihalomethanes (THMs) are a DBP of chlorine disinfection and are classified as Volatile Organic Chemicals (VOCs). Rising THM levels in raw water are increasing the use of chloramine as the preferred disinfectant. In this chapter, we will discuss chloramine disinfection and the associated challenges that come with its implementation. After reading this chapter, you should be able to:

- explain why chloramine treatment has been employed, (hint: DBP formation);
- describe the use of ammonia in water treatment;
- apply breakpoint chlorination; and
- explain risks of nitrification.

WHY USE CHLORAMINES?

As discussed, chlorine has been used with great effectiveness in water treatment for many years in the United States. However recently, many water agencies have been switching to chloramine treatment. Now here is the twist; they have done it because they must, not because they necessarily want to. When natural organic matter reacts with chlorine, it can result in the formation of DBPs, specifically Trihalomethanes (THM) and Haloacetic acids (HAA5). It is believed that long term exposure to these DBPs may lead to cancer.

Because of the implementation of the Stage 2 DBP Rule in 2012, many water agencies could no longer meet the regulatory limits established if they continued using chlorine as a primary disinfectant. To continue using chlorine alone, enhanced coagulation would have to be used but its effectiveness is limited. Carbon or GAC absorption is also a solution but it is very expensive, and thus not employed by larger water treatment facilities. The other option is to limit contact with the water and chlorine, but this is limited by the chlorine demand. The last and most effective option is to use chloramines.

Chloramine treatment is also effective in limiting taste and odor problems in finished water. When free chlorine reacts with phenol it can cause taste and odor issues. Chloramine disinfection is not as strong a disinfectant as free chlorine, chlorine dioxide, or ozone, but it does leave the longest lasting residual in finished water. Because of chloramines weaker disinfecting power, it is often added just before the treated water enters the clear well for storage. If implementing this method, the operator must ensure the THM levels are low enough as not to violate any regulations. Determining the most effective way to treat drinking water while remaining in compliance is a complex and difficult task.

CHLORAMINE CHEMISTRY

Chlorine reacts with several substances in water including dissolved organic matter, particulate organic matter, iron, nitrite, sulfide, and ammonia. It reacts by taking away an electron from them. Ammonia in the water supply is undesirable as it strips away the chlorine residual which then requires the need to use more Chlorine. What makes chloramine treatment so effective is chlorine's quick formation with ammonia (NH_3). (Ammonia is a compound of Nitrogen and Hydrogen.)

$CL_2 + NH_3 \rightarrow NH_2Cl + HCl$ (monochloramine is expressed as NH_2Cl)

The unit weight of chlorine is 70 and the unit weight of Nitrogen is 14. When chloramine treatment is employed, the ratio of chlorine to ammonia will always be 5:1 because 5 mg/L of chlorine will always combine with 1.0 mg/L of ammonia. (70 ÷ 14 = 5) You will often hear monochloramines referred to as combined chlorine due to this reaction.

Below is a list of terms dealing with chloramine disinfection:

- **free chlorine**: Cl_2 (Free chlorine can refer to gaseous, sodium hypochlorite, or calcium hypochlorite.) If using hypochlorite, remember you must dose the water to achieve 100 percent free chlorine.
- **monochloramine**: NH_2Cl or combined chlorine. Chloramine with the least taste and odor problems.
- **free ammonia**: NH_3 Ammonia is measured as nitrogen.
- **chlorine: ammonia ratio:** Total chlorine to total ammonia nitrogen. You will always target a 5:1 ratio to avoid excess free chlorine or free nitrogen in the water supply.

BREAKPOINT CHLORINATION

The **breakpoint chlorination curve** is the visual representation of chlorine's ability to react with a variety of compounds to form a combined chlorine residual or to completely react with compounds to form a free chlorine residual. When using free available chlorine as a disinfectant we want to stay out of the combined curve. Some water agencies buy imported water that has a combined residual. To treat the water more effectively or eliminate the possibility of nitrification, some of these agencies add chlorine to "break" over to a free chlorine residual. We will discuss nitrification in greater detail later in this chapter.

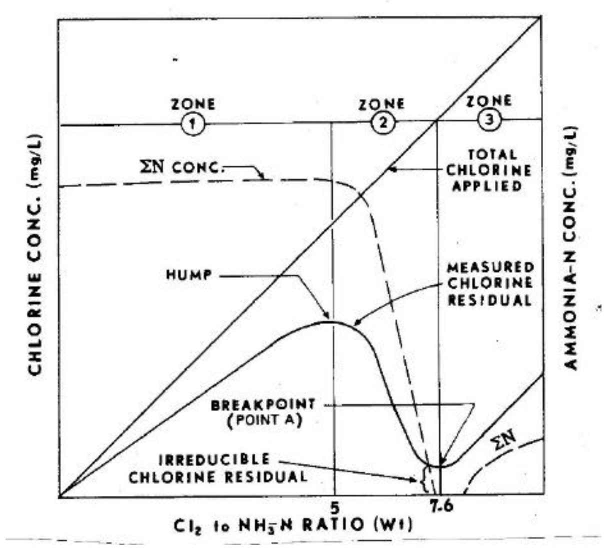


Figure 9.1: The breakpoint chlorination curve. This curve represents chlorine's ability to have either a combined residual or a free residual.[37]

A common problem that operators run into when using combined chlorine is "breaking over" to free chlorine by misdiagnosing problems in the treatment plant. For example, an operator is looking at a Supervisory Control and Data Acquisition (SCADA) screen. (SCADA is the computer system that monitors and controls the plant.) For the sake of ease, we will call this Operator #1. An operator notices the chlorine effluent residual is beginning to drop. Operator #1 was not aware that the previous operator (Operator #2) had raised the chlorine dose a few hours before. With the added chlorine dose, the chlorine residual was "lowering" as it got closer to breaking over. If Operator #1 panics and raises the chlorine dose again the combined chlorine residual will lower even further.

The important thing to remember is there are many things to look at if your chlorine dose is lowering. It may very well be an issue with your chlorine feed, but there are many other options to consider. If you check your chlorine feed system and everything is functioning normally, you may have an issue with the ammonia feed system. Many modern water treatment facilities have calculations built into the SCADA system that make chloramine dosing easier. Make sure to go to the screen with the chlorine: ammonia: ratio to make sure that it is set up correctly.

Lastly, free chlorine is always the preferred disinfectant as it is 25 times stronger a disinfectant than chloramines. However, chloramines last much longer in the distribution system. There are several factors that may lead to a lowered chlorine residual. An increase in biological growth is possible, but you should see other signs such as an increase in turbidity. The most common problem in chloramine treatment with a decreasing chlorine residual is operator error or an issue with the water treatment process.

[37] Image by the NSW Department of Premier and Cabinet is licensed under CC BY 4.0

NITRIFICATION

Nitrification is a process in which bacteria reduces ammonia and organic nitrogen in treated water into nitrate and then nitrite. This condition usually occurs during the summer months when water temperatures are higher. It can also occur during the improper turnover of reservoirs, when there are high levels of ammonia, and in dark environments, a typical condition for most water reservoirs.

This condition is one of the drawbacks of chloramine treatment. Nitrate and nitrite are inorganic chemicals regulated by primary drinking water standards. The MCL (Maximum Contaminate Level) for nitrate is 10 ppm and the MCL for nitrite is 1 ppm. High nitrate and nitrite levels in drinking water can lead to methemoglobinemia also known as “blue baby syndrome.” This condition effects infants under six months old that consume water contaminated with nitrates and nitrites. The infant’s blood is not able to carry enough oxygen to blood cells and tissue within their body.

The condition of nitrification is a reoccurring cycle that can lead to the total loss of chloramine residual in the distribution system and in water storage tanks. If this was to occur, all the water in the system would have to be dumped and it would be a total loss of money for your agency, but it could lead to an outbreak of methemoglobinemia. The cycle is below:

Chloramine decay→ Release of ammonia→ oxidation of ammonia to nitrite from oxidizing bacteria → Biomass increase → (back to chloramine decay until there is a possibility of total loss of residual)

Some early indicators of nitrification are:

- lowering chloramine residual
- increase in bacterial heterotrophic plate counts
- excess ammonia in the treated water
- total coliform positive samples

In summation, nitrification can cause a variety of problems and violations within the water system. What can we as operators do to minimize any chance of nitrification from occurring? There are a few steps every operator can take to avoid nitrification. First, you want to minimize free ammonia in treated water. Sampling and equipment around the treatment plant will help operators determine if there is too much free ammonia in the treated water.

Second, operators should always maintain a good chlorine residual. Isn’t that the name of the game? Sure, but it is easier said than done in some cases. Many water treatment companies will lower their target chlorine residual in the summer to save on costs because the disinfectant works more efficiently during the summer months. It is a good practice in theory, but not necessarily the best practice if you are working with chloramines and trying to combat nitrification.

Reducing water age is the third step operators can use to combat nitrification. This can be done by cycling reservoirs during the summer months and taking reservoirs out of service during the winter when water demands are lower. Distribution operators are continually balancing maintaining a good amount of water for fire flow and demand, but also cycling reservoirs to fight nitrification. A good practice is to take all the reservoirs in the distribution system and divide it into thirds. At any given point during the day 1/3 of the reservoirs are full, 1/3 are in the middle range, and 1/3 are in the lower range. This allows operators to cycle water while also keeping water in the system.

The last step is to keep the water system clean. This can be accomplished by flushing dead ends to prevent lower chlorine residuals at the end of the distribution system. Boosting chlorine by adding it directly to a reservoir is also an option but not always the best practice. The problem with this method is it could lead to short circuiting. Chlorine must mix adequately to be effective. Mixing can be accomplished by adding mechanical mixers in the reservoir to keep water moving and prevent short circuiting. Chlorine can also be added to the inlet of the reservoir, so the water pressure acts as a mixer.

Figure 9.2: Hydrant flushing is a method that can be used to get rid of stagnant water at the ends of a distribution system. Stagnant water can lead to lower chlorine residuals and possible nitrification[38]

In summary, the use of chloramines as a disinfectant is being employed by many water agencies in the United States to prevent DBP formation. It is not the most ideal disinfectant available, but it does have some advantages. Chloramine disinfection limits DBP formation and has a longer lasting disinfectant residual. This can be useful for larger systems where water must travel great distances to get to storage.

[38] Image is licensed under CC0

The drawbacks include the difficulty in effectively managing the breakpoint chlorination curve and managing nitrification. Because of advancements in water quality testing and more stringent regulations with DBPs, chloramine treatment is and will continue to be a more popular option in water treatment.

Key Terms

- **breakpoint chlorination curve** – the visual representation of chlorine's ability to react with a variety of compounds to form a combined chlorine residual or to completely react with compounds to form a free chlorine residual
- **chlorine: ammonia ratio** – Total chlorine to total ammonia nitrogen
- **free ammonia** – NH_3 Ammonia is measured as nitrogen
- **free chlorine** – Cl_2 (Free chlorine can refer to gaseous, sodium hypochlorite, or calcium hypochlorite)
- **monochloramine** – NH_2Cl or combined chlorine; chloramine with the least taste and odor problems
- **nitrification** – a process in which bacteria reduces ammonia and organic nitrogen in treated water into nitrate and then nitrite

CHAPTER REVIEW

1. What is the target chlorine : ammonia ratio?
    a. 2:1
    b. 3:1
    c. 4:1
    d. 5:1

2. What is the atomic weight of chlorine?
    a. 70
    b. 14
    c. 65
    d. 20

3. Which disinfectant has the longest lasting residual?
    a. ozone
    b. chlorine
    c. chloramine
    d. chlorine dioxide

4. What are some of the early indicators of nitrification?
    a. lowering chlorine residual
    b. excess ammonia in treated water
    c. raise in bacterial heterotrophic plate counts
    d. all of the above

5. What are THMs classified as?
    a. turbidity
    b. radiological
    c. volatile organic chemicals
    d. salts

6. Which method can operators employ to combat nitrification?
    a. lower residual chlorine target
    b. keep reservoir levels static
    c. minimize free ammonia in treated water
    d. increase water age

7. How many times stronger is chlorine compared to monochloramine?
    a. 25 times
    b. 20 times
    c. 15 times
    d. 5 times

CHAPTER 10 – THE LABORATORY

Many larger agencies have a dedicated staff of laboratory personnel that handle a lot of the day to day water quality analysis, but water treatment operators still play a key role. State regulations require operators to take samples throughout the day to ensure monitoring equipment throughout the plant is running correctly. After all, the operator is the person in charge of running the plant, monitoring chemical feeds, and performing routine plant checks to ensure the system is running smoothly. A laboratory scientist can run all the tests in the world, but since they are not the ones running the plant, a lower chlorine residual may not stand out to them. The responsibility falls squarely on the shoulders of the operator.

After reading this chapter, you should be able to:

- identify equipment in the laboratory;
- describe laboratory safety;
- explain water quality testing; and
- identify contaminants tested in the laboratory and throughout the treatment plant.

LABORATORY INSTRUMENTS AND EQUIPMENT

In the lab you will find a variety of beakers, flasks, dilution bottles, and graduated cylinders. A lot of these instruments look the same or similar, but they all have a unique job and purpose. Beakers range in size from 25 to 4000 milliliters (mL). They are used to mix samples during chemical analysis. A burette is a long skinny tube-like glass receptacle used to measure and disperse liquid. Flasks have a narrow neck and are round at the bottom. Each kind of flask serves a different purpose.

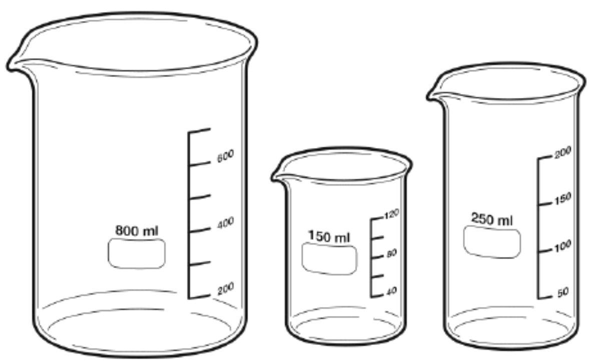


Figure 10.1: Beakers[39]

Figure 10.2: Volumetric flask[40]

[39] Image by Xavax is in the public domain

[40] Image by Lucasbosch is licensed under CC BY-SA 3.0

Graduated cylinders are tall and cylindrical and range in size from 10 mL-4000 mL. They are used to measure liquid, but not with accuracy. For example, they can be used during a chlorine test to gather a general volume of water. If you need an exact amount, it should be measured with a pipette or other similar and accurate liquid measuring device. The pipette measures a liquid with 100 percent accuracy.

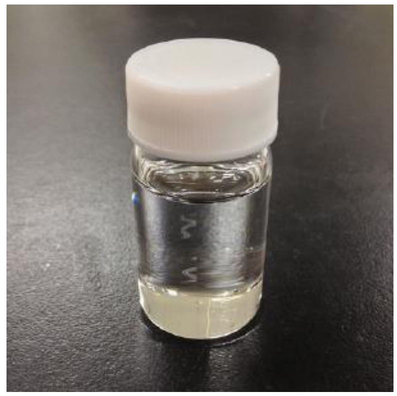


Figure 10.3: Sample Bottle[41]

You will find sample bottles in any laboratory. The bottles can be made of plastic or glass. They are used to store water for future lab tests and not used for measuring liquid. Sample bottles are used to collect bacteriological samples and for organic chemical analysis. The bacteriological bottle is one of the most important sample bottles you find in a lab. They are made of plastic and are 100 mL. Water treatment operators must take bacteriological samples per the Total Coliform Rule. These tests will be performed daily in the lab and throughout the distribution system based on your coliform sampling plan.

Figure 10.4: Graduated Cylinder[42]

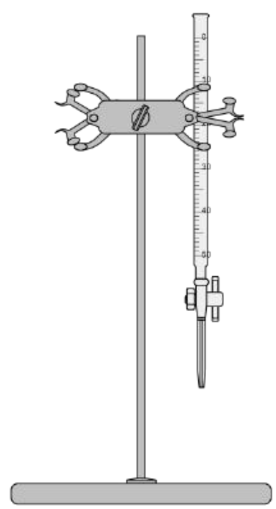


Figure 10.5: Burette[43]

---

[41] image by Σ64 is licensed under CC BY-SA 3.0
[42] Image by Lilly_M is licensed under CC BY-SA 3.0
[43] Image by Roland1952 is licensed under CC BY-SA 3.0

OTHER ITEMS FOUND IN THE LABORATORY

Incubators will be found in every lab at a water treatment plant. They are used to hold a temperature for bacteriological cultures. There are two types of incubators used, dry heat and water baths. Common uses for incubators include coliform testing, multiple tube testing, and heterotrophic plate counts. Ovens are other pieces of equipment found in the lab. Autoclaves, for example, are used to sterilize glassware items but can also be used to sterilize material that has been contaminated from perhaps a positive coliform test. Refrigerators are used to store samples for future testing and to store chemicals used for water quality testing. These refrigerators are for work use only and should not be used to store food and beverages.

LABORATORY SAFETY

Operators should always be aware of safety regardless of where they are at the treatment plant. The laboratory should be treated no differently than if an operator was changing chlorine cylinders. There are chemicals that are combustible and others that can cause severe burns if they are exposed to skin. Some common safety equipment found in water treatment plant laboratories:

- Eye protection - Eye protection should include safety goggles, safety glasses, or face shields. It is not recommended to wear contact lenses if working with dangerous chemicals. Prescription safety eyewear is available. You only have one set of eyes, so it is important to protect them. Water laboratories have liquids and solids that can easily penetrate your eyes if you are not wearing the proper PPE (personal protective equipment).
- Safety Showers/Eyewash Bottles - In the event something gets in your eyes, every lab is equipped with a safety shower. The shower should have a pull lever and an eye wash sink.
- Fire Extinguisher - Fire extinguishers are located throughout any building in the United States. Fire extinguishers are meant to put out very small fires very quickly. Most water treatment companies will provide formal training on proper use of a fire extinguisher. In the event you cannot put a lab fire out with the use of an extinguisher, exit the room right away and call the fire department.

10.6: Emergency eyewash and shower[44]

Laboratories use a variety of meters for water quality testing. Although meters are located throughout the treatment plant, the meters in the lab are used to verify that equipment throughout the treatment plant is functioning correctly. The most common meters used by water treatment operators are pocket colorimeters for chlorine testing in the field, turbidity meters, and pH meters. Pocket colorimeters are great to be used in the field, but the results are not reportable. For compliance purposes you must use an electric colorimeter or photometer.

pH meters and turbidimeters are used to verify equipment is working throughout the plant. At a minimum an operator will run labs on turbidity, chlorine residual, water temperature, and pH. All these parameters are required for CT compliance and verification. These measurements are important in ensuring the treatment plant is operating in compliance with the surface water treatment rule.

MICROBIOLOGICAL TESTING

Microbiological testing is probably the most important testing done by water treatment professionals. As discussed at length in this text, treatment water operators aim to remove and deactivate pathogenic organisms from drinking water through filtration and disinfection. Water regulations require 3 Log removal and deactivation of *Giardia* and 4 log removal and deactivation of viruses. Bacteria fall in the middle of *Giardia* and viruses. Therefore, it is safely assumed bacteria will be removed and deactivated along the same process.

---

[44] Image by Korn966 is licensed under CC BY-SA 4.0

Water professionals test for microbiological agents by testing for the indicator organism coliform. Coliform bacteria cause no harm to humans but are generally present when pathogens are present in the water. The reason coliforms have been used to identify contaminated water for over 100 years is because they are always present in contaminated water. Even if there is no fecal contamination, they are still present. They survive longer in water than pathogens and they are easy to identify with proper testing. When a positive sample is identified, we assume the water is contaminated until it can be proven otherwise.

Water treatment facilities use four different tests for coliform monitoring. The easiest, least expensive, and the most common method for coliform testing is the presence absence test (P-A). Both the P-A and **multiple tube fermentation (MTF)** tests work because coliform produces gas from the fermentation of lactose within 24-48 hours. The MTF method uses three steps for the test. It includes the presumptive, confirmed, and completed test cycle. The presumptive test is accomplished in 24 hours. Samples are incubated at 35 degrees Celsius for 24 hours and then checked to see if a gas bubble has formed or if the sample is cloudy. You want to see no bubble or gas. The samples are then incubated for another 24 hours. If gas does not form, the test is over, and the sample is absent. If there is a gas bubble, you move on to the confirmed test.

The confirmed test verifies the sample is positive from coliform and not another type of bacteria. Brilliant Green Lactose Vile is added to the sample and then incubated for another 48 hours. The same method is used. The lab technician or operator checks to see if gas is produced during the incubation period. The minimum requirement for water treatment operations is the presumptive and confirmed test. The completed tests are rarely used except for quality control by laboratory personnel. In the event of a positive confirmed test, coliform bacteria violation protocol will go into effect.

The **P-A** method is the most common method for treatment operators and field sampling staff. The bottles are easily transferred in an ice chest and the set-up is very simple. This method is commonly referred to as the Colilert method. The test uses a 100 mL plastic sample bottle. A nutrient is added to the sample, which is then incubated for a period of 24 hours at 35 degrees Celsius. The nutrient will cause the water to turn yellow if coliforms are present. In the event of a positive test, the bottle can be placed behind a fluorescent light that will turn a blue color which indicates fecal E. coli contamination.

The other two bacteriological tests include **MMO-MUG** and the **membrane filter method**. The MMO-MUG tests come with the testing agent already in the vials. A 10 mL sample is simply added to the vial. As with the P-A test, samples positive for coliform will turn yellow and for fecal contamination will turn blue. The membrane process begins with filtering 100 mL of water through a membrane filter. Then the sample is added to a petri dish and incubated for a 24-hour period. Coliform positive samples turn a red-pink color. Confirmative tests require incubation of a broth for another 24 hours.

PHYSICAL WATER QUALITY

Operators test the water for both physical properties and contaminants that will cause harm to humans. There are secondary standards related to many of the physical test's operators perform. Acidity is the ability to neutralize a base. Alkalinity is the ability of water to neutralize acid. The reason operators are concerned with the acidity and alkalinity of drinking water is different pH scales have different effects on water treatment. When acids are added to water, they lower the pH of the water. A strong base may need to be added to boost the pH. Operators want a small amount of calcium carbonate present in the water to deposit around the pipes of the distribution system. This helps combat corrosion.

When we think of water drinkability, we might think of color, taste, odor, and temperature. The physical aesthetic of the water matters and impacts our desire to drink the water. The color of the drinking water may indicate water with higher levels of organic compounds and water with THMs.

Taste and odor issues in treated drinking water are hard to test. Many customers complain of a strong chlorine smell in their drinking water. Taste and odor problems can come from organic matter, chlorine, dissolved gases, and even industrial wastes. The threshold odor test is measured on the TON scale. (Water sample of 100 mL + dilution divided by 100 = TON.) Water registering as a 3 will most likely draw complaints from customers.

Water temperature plays a key role in water treatment because disinfectants work better at higher temperatures. However, nitrification occurs during the warmer months of the year, so the water temperature must be carefully managed. Water agencies in colder regions of the country must deal with freezing conditions within their treatment and distribution system. During the winter even in warmer regions, lake turnover can cause vast changes in water quality.

High levels of turbidity can signify major issues within the treatment plant. Therefore, turbidity is used to verify how efficiently the treatment plant is operating. High turbidity values may indicate higher levels of organic and inorganic matter. Pathogenic organisms can hide behind turbidity and render disinfection ineffective. Turbidity is measured in the lab with a nephelometric counter. A light source is added and in the presence of turbidity the light scatters producing higher numbers with greater amounts of turbidity.

The final two water quality testing procedures most performed by water treatment operators are chlorine and pH. The chlorine or chloramine feed system is one of the most critical components of a water treatment plant that operators monitor through online testing and grab samples.

The measurement of the hydrogen ion concentration in water is **pH**. The pH scale ranges from 1- 14 with 1 being the most acidic and 14 the most basic. The higher ends of both ranges produce the most corrosiveness. 7 is considered neutral. Do not confuse pH with acidity or alkalinity. It is important to monitor pH because the pH is used to control many chemical reactions in the treatment plant including coagulation, disinfection, corrosion control, and the removal of ammonia. pH also plays a key role in the CT calculation.

Key Terms

- **incubator** – a device used to hold a temperature for bacteriological cultures; two types, dry heat, and warm baths, are used for coliform testing, multiple tube testing and heterotrophic plate counts
- **membrane filter method** – a method of testing for coliform that filters 100 mL of water through a membrane filter and then adds the sample to a petri dish and incubates it for a 24-hour period
- **MMO-MUG** – a method of testing for coliform that comes with the testing agent already in the vials
- **multiple tube fermentation (MTF)** – method of testing for coliform; assumes that coliform produces gas from the fermentation of lactose within 24-48 hours
- **P-A method** – most common method for treatment operators and field sampling staff to test for coliform; a nutrient is added to a sample in a 100 mL sample bottle; assumes that coliform produces gas from the fermentation of lactose within 24-48 hours
- **pH** – the measurement of the hydrogen ion concentration

CHAPTER REVIEW

1. Which is an organism used to indicate the possible presence of E. coli contamination?
    a. *Cryptosporidium*
    b. *Giardia*
    c. Coliform
    d. Brilliant Green Vile

2. Which is a name for the presence-absence (P-A) test used for microbiological testing?
    a. multiple tube fermentation
    b. membrane filtration
    c. confirmed test
    d. Colilert

3. When testing for coliform bacteria with the multiple tube fermentation (MFT) method what is the best indicator for a positive test?
    a. color change
    b. gas bubble formation
    c. formation of a cyst
    d. formation of turbidity

4. Coliform bacteria share many characteristics with pathogenic organisms. Which of the following is not true?
    a. They survive longer in water
    b. They grow in the intestines
    c. There are less coliform than pathogenic organisms
    d. They are still present in water without fecal contamination

5. What is the second step in the multiple tube fermentation test?
    a. presumptive test
    b. negative test
    c. completed
    d. confirmed

6. What is the removal and deactivation requirement for *Giardia*?
    a. 2 Log
    b. 3 Log
    c. 4 Log
    d. There is no requirement

7. Which method is used in the multiple barrier approach to water treatment??
    a. filtration
    b. coagulation
    c. disinfection
    d. a and c

8. Which best describes a pH reading of 7?
    a. slightly acidic
    b. acidic
    c. basic
    d. neutral

9. Which might a higher than normal turbidity reading mean?
    a. a change in water quality
    b. Nothing. Keep operating as normal
    c. microbiological contamination
    d. Both A & C

10. What is the ingredient used during the second multiple tube fermentation test?
    a. Colilert
    b. MMO/MUG
    c. Brilliant Green Vile
    d. chlorine

APPENDIX 1: INTRODUCTION TO WATER MATH

Mathematics is a key component in water treatment. Operators use conversion tables and basic algebra to complete many daily tasks. Charts are available on the State Water Resources Control Board website that assist operators with most calculations you would find on the state exams or while on the job. Below is a list of basic units and their respective conversion factors:

Table 1 - Units and Conversion Factors

Measurement	Equivalent
1 cubic foot of water	62.3832 lbs
1 gallon of water	8.34 lbs
1 liter of water	1,000 grams
1 mg/L	1 part per million (ppm)
1 ug/L	1 part per billion (ppb)
1 mile	5,280 feet or ft
1 yard	3 feet or ft
1 yard^3	27 ft^3
1 acre	43,560 square feet or ft^2
1 cubic foot or ft^3	7.48 gallons or gal
1 gallon	3.785 Liters or L
1 L	1,000 milliliters (mL)
1 pound	454 grams

SIMPLIFYING FRACTIONS

Simplified fractions are fractions expressed in their lowest terms. This simply means that the fractions can no longer be divided by any other number.

In proper fractions, if the numerator and denominator can be divided by the same number, the fraction can be simplified.

Example: Simplify the following fraction.

$$\frac{2}{4}$$

In this example, both the numerator and the denominator are each divisible by the number 2. All even numbers are divisible by 2.

$$\frac{2 \div 2}{4 \div 2} = \frac{1}{2}$$

Therefore, two-fourths $\left(\frac{2}{4}\right)$ and one-half $\left(\frac{1}{2}\right)$ represent the same number or value but are expressed differently. They are called **equivalent fractions** and one-half $\left(\frac{1}{2}\right)$ is a simplified form of two-fourths $\left(\frac{2}{4}\right)$.

Note that any number divided by the same number is equal to one $\left(\frac{2}{2} = 1\right)$ and any number divided by one is unchanged. So, dividing the numerator and the denominator by 2 simplifies the fraction, but doesn't change the value.

You may need to divide a fraction multiple times in order to simplify it.

Example: Simplify the following fraction.

$$\frac{8}{12}$$

In this example, both the numerator and the denominator are each divisible by the number 2. But, $\frac{4}{6}$ can still be simplified.

$$\frac{8 \div 2}{12 \div 2} = \frac{4}{6}$$

$$\frac{4 \div 2}{6 \div 2} = \frac{2}{3}$$

This fraction can also be simplified in one-step by dividing both the numerator and the denominator by 4 instead of 2. Both solutions provide the same answer.

$$\frac{8 \div 4}{12 \div 4} = \frac{2}{3}$$

To simplify an improper fraction**,** the denominator is divided into the numerator to create a mixed number. The remainder is then written as a fraction.

Division problems are typically written as

$$24 \div 4 \quad \rightarrow \quad \frac{24}{4} \quad \rightarrow \quad 4\overline{)24}$$

In each of these expressions, 24 is called the dividend, 4 is called the divisor, and the solution is called the quotient.

$$\begin{array}{r} 6 \rightarrow \text{quotient} \\ \text{divisor} \rightarrow 4\overline{)24 \rightarrow \text{dividend}} \end{array}$$

$$\begin{array}{ccccccc} 24 & \div & 4 & = & 6 \\ \text{dividend} & \div & \text{divisor} & = & \text{quotient} \end{array}$$

Example: Simplify the following fraction.

$$\frac{14}{3}$$

$$\frac{14}{3} \rightarrow 3\overline{)14}^{\,4}$$ First, divide the numerator (14) by the denominator (3).

$$\begin{array}{r} -\ 12 \\ \hline 2 \end{array}$$

$$\frac{14}{3} = 4\frac{2}{3}$$ The remainder, 2, is written as a fraction over the original denominator of 3, $\frac{2}{3}$.

Remember: The fractional portion of the resulting mixed number may also need to be further simplified.

Example: Simplify the following fraction.

$$\frac{18}{4}$$

$$\begin{array}{r|l} & \;\;4 \\ 4\,) & 18 \\ & -16 \\ \hline & \;\;2 \end{array} \quad = 4\frac{2}{4}$$

$4\frac{2}{4}$ The fractional part of this mixed number needs to be simplified.

$$\frac{2}{4} \div \frac{2}{2} = \frac{1}{2}$$

$$4\frac{2}{4} = 4\frac{1}{2}$$

MULTIPLYING FRACTIONS

Multiplying and dividing fractions are common practices when solving water-related math problems. However, the process may not appear to be the multiplication and division of fractions and is commonly referred to as "unit conversion" or unit dimensional analysis. The example below demonstrates this process and will be discussed in more detail later in this text.

$$\frac{2\text{ sqft}}{1} \times \frac{3\text{ ft}}{1\text{ sec}} = \frac{6\text{ cf}}{\text{sec}}$$

For now, ignore the units and focus on solving the math. Look at the above problem as a fraction multiplication problem. Yes, both 2 over 1 and 3 over 1 are simply 2 and 3, but it helps to illustrate the process by looking at them as fractions.

$$\frac{2}{1} \times \frac{3}{1} = \frac{6}{1}$$

When multiplying fractions, the numerators are multiplied by each other and the denominators are multiplied by each other. In other words, the numbers are multiplied straight across. So, in the example above, 2 x 3 = 6 and 1 x 1 = 1. The resulting answer is 6 over 1 or more simply put, 6. However, when "units" are introduced, you can't just say the answer is "6." Always remember to simplify as necessary. Look at a couple other examples below:

Example: $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$

In this example, if you multiply the numbers straight across, you would multiply 1 times 1 and then 2 x 2. The resulting answer is 1 over 4 or one-fourth.

Example: $\frac{2}{3} \times \frac{4}{6} = \frac{8}{18}$

$$\frac{8 \div 2}{18 \div 2} = \frac{4}{9}$$

This example is the same process. Multiply the 2 and 4 to get 8 and then multiply the 3 and 6 to get 18. The resulting answer is 8 over 18 or eight eighteenths. Remember that you always need to simplify a fraction to its lowest terms. In order to simplify, you need to find a number that will go into both 8 and 18. Since 2 will go into both, you can simplify the answer to 4 over 9 or four-ninths.

Note that sometimes you can simplify the fractions before you multiply. This is called cross canceling. Look for any number that goes into both the numerator and the denominator. In the example above, 2 goes into both the 2 in the numerator of the first fraction and the 6 in the denominator of the second fraction.

$$\frac{2}{3} \times \frac{4}{6} = \frac{\cancel{2}^{1}}{3} \times \frac{4}{\cancel{6}_{3}} =$$

$$\frac{1}{3} \times \frac{4}{3} = \frac{4}{9}$$

When you cross cancel, you simplify the two-thirds times four-sixths to one-third times four-thirds. Then you multiply the 1 times 4 (straight across the numerators) and the 3 times 3 (straight across the denominators) to get an answer of four ninths.

When multiplying a whole number with a fraction, you must first convert the whole number into an improper fraction and then, multiply. Be sure to cross cancel if possible and always simplify the solution when possible. Placing a whole number over a 1 is an important step not only in solving these types of fraction problems, but it will also be a helpful tool later in this text.

Example: $5 \times \frac{3}{5} = \frac{5}{1} \times \frac{3}{5}$

$$\frac{\cancel{5}^{1}}{1} \times \frac{3}{\cancel{5}^{1}} = \frac{3}{1} = 3$$

The same rules apply when multiplying mixed numbers. The mixed number must be converted to an improper fraction before you can multiply. To convert a mixed number to an improper fraction, you must first multiply the whole number by the denominator of its fraction. Then, add the numerator to the product and put that total number over the denominator. Be sure to cross cancel and simplify when possible. Note: Never leave an answer as an improper fraction.

Example: $1\frac{1}{2} \times 2\frac{3}{4}$

$$1\frac{1}{2} \rightarrow (1 \times 2) + 1 \rightarrow \frac{3}{2}$$

$$2\frac{3}{4} \rightarrow (2 \times 4) + 3 \rightarrow \frac{11}{4}$$

$$\frac{3}{2} \times \frac{11}{4} = \frac{33}{8}$$

$$\frac{33}{8} \rightarrow 8\overline{\smash{)}\,33\,}^{\;4} \quad \begin{array}{r} 33 \\ -\,32 \\ \hline 1 \end{array} = 4\frac{1}{8}$$

DIVIDING FRACTIONS

When dividing fractions, the good news is that we change the division problem to a multiplication problem in order to solve. To do this, you invert (flip upside down) the fraction on the right side of the division symbol, the divisor, in the equation. Then it becomes a multiplication problem. Simply invert and multiply!

Example: $\frac{2}{5} \div \frac{1}{2} \rightarrow \frac{2}{5} \times \frac{2}{1} = \frac{4}{5}$

Example: $\dfrac{\frac{4}{9}}{\frac{8}{9}}$ This example reads $\frac{4}{9}$ divided by $\frac{8}{9}$.

However, after you invert and multiply, it becomes

$$\frac{4}{9} \div \frac{8}{9} \rightarrow \frac{4}{9} \times \frac{9}{8}$$

$$\frac{4}{9} \times \frac{9}{8} = \frac{\cancel{4}^{1}}{\cancel{9}_{1}} \times \frac{\cancel{9}^{1}}{\cancel{8}_{2}} =$$

$$\frac{1}{1} \times \frac{1}{2} = \frac{1}{2}$$

After inverting the fraction, you have a multiplication problem with all the same rules you previously applied when multiplying fractions. You need to change mixed numbers into improper fractions; you can cross cancel, and always remember to simplify if possible.

Example: $\frac{3}{8} \div \frac{12}{6} \rightarrow \frac{3}{8} \times \frac{6}{12}$

$$\frac{\cancel{3}}{\cancel{8}} \times \frac{\cancel{6}}{1\cancel{2}} = \frac{1}{4} \times \frac{3}{4} = \frac{3}{16}$$

In the example above, the 3 divided into itself once and into the 12 four times. Similarly, 2 divided into 6, three times and into 8, four times. Can you see a different way to cross cancel?

Remember that in order to cross cancel, you must first invert the divisor.

If the dividend or the divisor is a whole number, write it as a fraction before inverting and multiplying. Always remember to cross cancel and simplify if possible.

Example: $\frac{5}{8} \div 10 \rightarrow \frac{5}{8} \div \frac{10}{1} \rightarrow \frac{5}{8} \times \frac{1}{10}$

$$\frac{\cancel{5}}{8} \times \frac{1}{1\cancel{0}} \rightarrow \frac{1}{8} \times \frac{1}{2} = \frac{1}{16}$$

UNDERSTANDING DECIMALS

Numbers written with decimals is another way of expressing fractions. However, decimals are different than fractions in that decimals are based on 10. In that, one decimal place to the right of the whole number indicates *tenths*, two decimal places to the right of the whole number indicates *hundredths*, three decimal places to the right of the whole number indicates *thousandths*, etc.

Example:	0.1	one is in the tenths place
	0.01	one is in the hundredths place
	0.001	one is in the thousandths place
	0.0001	one is in the ten thousandths place

Decimals can easily be written as fractions by using the number to the right of the decimal point as the numerator and then using a 10, 100, 1,000, 10,000, etc. as the denominator. Determining which "base-ten" number to use as the denominator is determined by the number of digits there are to the right of the decimal point.

Example:	$0.1 \rightarrow \frac{1}{10}$	one tenth
	$0.01 \rightarrow \frac{1}{100}$	one hundredth
	$0.001 \rightarrow \frac{1}{1{,}000}$	one thousandth
	$0.0001 \rightarrow \frac{1}{10{,}000}$	one ten-thousandth

ROUNDING

Rounding is another important process to understand and properly use in waterworks mathematics. Decimal places can be carried out to the ten-thousandths place and further if needed. However, in waterworks mathematics we seldom carry decimal places much further than the hundredths place, unless we are working in water quality. The rule to follow is to "round" the decimal to the furthest decimal place in the actual question. Look at the examples below:

Example:	2 × 2 = 4	Since both numbers you are multiplying are whole numbers, you would leave the answer as a whole number.
	2.0 × 2.0 = 4.0	The answers may look like they are the same. After all, doesn't 4 and 4.0 equal the same number? The short answer is yes. However, 4.0 is more accurate than 4. Why? Because 4.0 is rounded to the tenths place and is saying the value is no more than 4 and 0 tenths. When we round the first answer, 4 can be 4.1, 4.2, 4.3, or 4.4. We don't know, since the whole numbers are expressed as whole numbers and are not rounded to the nearest tenth. In this example, both numbers being multiplied are rounded to the nearest tenth. Therefore, we round the answer to the nearest tenth.
	2.0 × 2 = 4.0	This answer is also rounded to the nearest tenth since one of the numbers being multiplied is rounded to the nearest tenth. However, the second example is still the most accurate because both terms being multiplied are provided to the tenths place.

Now let's look at how we round. The rule is simple. You look at the number to the right of the place you want to round. If you want to round to tenths, you would look at the number in the hundredths place. If you want to round hundreds, you look at the number in the tens place, etc. If that number (the one to the right of the place you want to round) is less than or equal to 4 meaning 0, 1, 2, 3, or 4, you round down and the number in the place you want to round remains the same. If the number is greater than or equal to 5 (5, 6, 7, 8, or 9), then you round up and the number in the place you want to round goes up by one.

Examples: Round to the nearest whole number.
1.2 rounds to 1
1.24 rounds to 1
1.25 rounds to 1

In each of these examples, we are rounding to the whole number. Therefore, we look at the tenths place or the number to the right of the place we are rounding to. In these examples the number in the tenths place is 2. Since 2 is less than or equal to 4, we round down to 1.

Examples: Round to the nearest tenths place.
1.2 rounds to 1.2
1.24 rounds to 1.2
1.25 rounds to 1.3

Now we need to look at the hundredths place or the number to the right of the tenths place in order to round to the tenths place. Since there is no hundredths place in the first example, the number stays at 1.2. In the second example, you would round down since the preceding number is ≤ 4 and in the third example, you would round up since the preceding number is ≥ 5.

USING UNIT DIMENSIONAL ANALYSIS

Units are the single most important component of many mathematical problems especially in the waterworks industry. If you are reporting a flow rate of 1,000, what does this mean? 1,000 gallons per minute? 1,000 cubic feet per second? Or, 1,000-acre feet per year? It is strongly recommended that you get in the habit of writing down the units for all the problems you are solving. Most of the problem solving in waterworks mathematics requires the conversion of units.

cfs – cubic feet per second
gpm – gallons per minute
MGD – millions of gallons per day
AFY – acre-feet per year

Unit Dimensional Analysis (UDA) is the key to solving many water-related mathematical problems. UDA is the process of converting units of one type (e.g. gallons) to another similar type (e.g. cubic feet). Setting up your UDA problem is the most important step of the conversion problem. By “stacking” your units, you create a visual representation of the problem and clearly show where units can be canceled. This cancellation of units is very similar to cross canceling or reducing of fractions.

Example: Convert seconds to days using UDA.

$$\frac{\text{sec}}{1} \times \frac{\text{min}}{\text{sec}} \times \frac{\text{hour}}{\text{min}} \times \frac{\text{day}}{\text{hour}}$$

If we break the problem up into segments you can see how the canceling of units occurs.

$$\frac{\cancel{\text{sec}}}{1} \times \frac{\text{min}}{\cancel{\text{sec}}} = \text{min}$$

In the above example, if we just do the first step you can see that canceling seconds will yield minutes as the result. By continuing the same process you can convert to the appropriate units.

$$\frac{\cancel{\text{sec}}}{1} \times \frac{\cancel{\text{min}}}{\cancel{\text{sec}}} \times \frac{\cancel{\text{hour}}}{\cancel{\text{min}}} \times \frac{\text{day}}{\cancel{\text{hour}}} = \text{day}$$

The reason seconds is set up over a “1” is because it is the units you are wanting to convert from and remember anything over 1 is that value.

Although multiple units can be converted in a single problem, convert one unit at a time. A common waterworks mathematics problem is the conversion from cfs to gpm. Cubic feet needs to be converted to gallons and seconds needs to be converted to minutes.

Example: Convert cfs to gpm.

$$\frac{\text{cf}}{\text{sec}} \rightarrow \frac{\text{gal}}{\text{min}}$$

Note that you will be converting similar units. This means that you will be converting **cubic feet** to **gallons** which are both units for volume and converting **seconds** to **minutes** which are both units of time.

There are two conversion factors that need to be used to perform this conversion. How many seconds are in a minute? How many gallons are in a cubic foot? There are 60 seconds in every minute and there are 7.48 gallons in every cubic foot.

$$\frac{1\text{ cf}}{\text{sec}} \times \frac{60\text{ sec}}{\text{min}}$$

The expression 60 sec per minute is a conversion factor that is an equality. The conversion factor is deliberately written with the 60 sec on top of the equality because it needs to cancel with the sec units in the 1 cfs.

$$\frac{1\text{ cf}}{\cancel{\text{sec}}} \times \frac{60\ \cancel{\text{sec}}}{\text{min}} = \frac{60\text{ cf}}{\text{min}}$$

Since the seconds cancel, we end up with cubic feet per minute (cfm).

Now let's look at converting cubic feet to gallons. Remember that there are 7.48 gallons in every cubic foot.

$$\frac{1\text{ cf}}{\text{sec}} \times \frac{7.48\text{ gal}}{\text{cf}} \quad \rightarrow \quad \frac{1\ \cancel{\text{cf}}}{\text{sec}} \times \frac{7.48\text{ gal}}{\cancel{\text{cf}}} = \frac{7.48\text{ gal}}{\text{sec}}$$

If you combine both conversions above, you can see how cfs is converted to gpm.

$$\frac{1\ \cancel{\text{cf}}}{\cancel{\text{sec}}} \times \frac{60\ \cancel{\text{sec}}}{\text{min}} \times \frac{7.48\text{ gal}}{\cancel{\text{cf}}} = \frac{448.8\text{ gal}}{\text{min}}$$

Example: How many gallons are there in a tank which holds 300 ft^3 of water?

$$\frac{300\ \cancel{ft^3}}{1} \times \frac{7.48\ \text{gal}}{1\ \cancel{ft^3}} = 2{,}244\ \text{gallons}$$

Example: Convert 48 inches to feet.

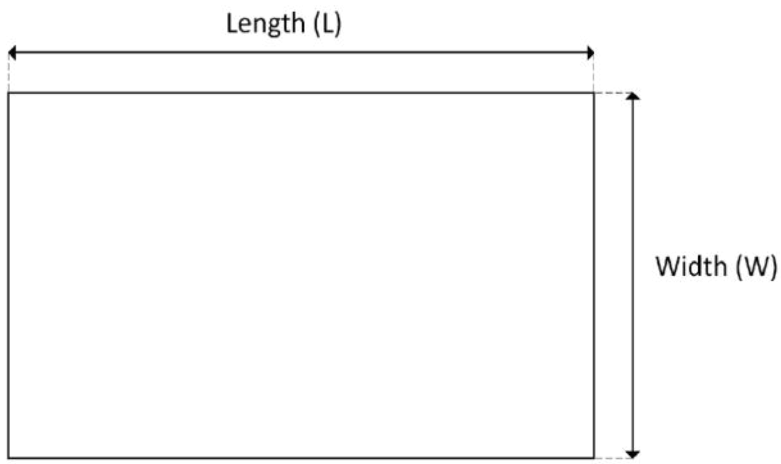
$$\frac{48\ \text{inches}}{1} \times \frac{1\ \text{ft}}{12\ \text{inches}} = \frac{4\ \text{feet}}{1} = 4\ \text{ft}$$

Note that the inches cancel out in this equation and you are left with feet.

AREA

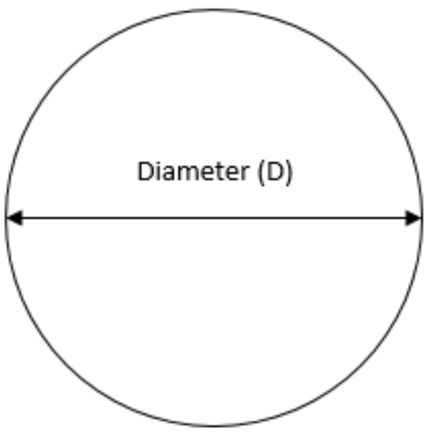
Area will be important for many applications in water math. It may be necessary to calculate the area of a tank that requires painting or an area of groundcover near equipment.

Rectangle



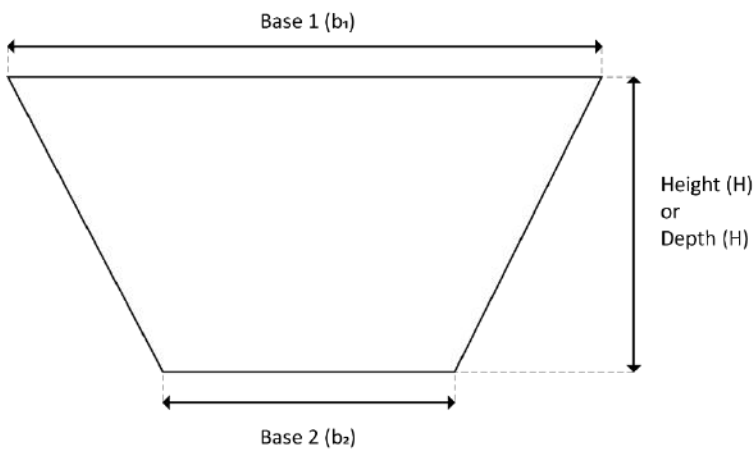
$$\text{Area} = L \times W$$

Circle



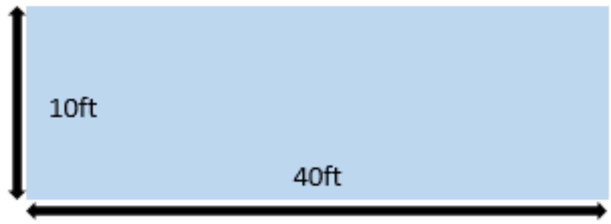
$$\text{Area} = 0.785 \times D^2$$

Trapezoid



$$\text{Area} = \frac{b_1 + b_2}{2} \times H$$

Example: A wall that is 10 ft wide and 40 ft in length needs to be painted. What is the total square feet of the wall?



Area = L $\times$ W

10 ft $\times$ 40 ft = 400 ft^2

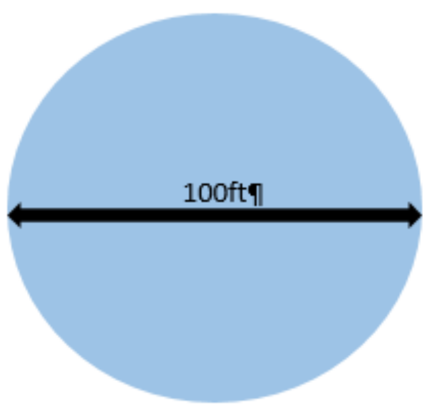
Example: What is the area of the top of a circular storage tank that is 100 feet in diameter?

Area of a Circle = 0.785 $\times$ D^2

= 0.785 $\times$ $(100\ ft)^2$

= 0.785 $\times$ 100 ft $\times$ 100 ft = 7,850 ft^2

Example: The top of a circular storage tank needs to be painted. It is 100 ft in diameter. Each gallon of paint covers approximately 200 square feet. How many gallons of paint will you need to buy?



Area of a Circle = 0.785 $\times$ D^2

= 0.785 $\times$ $(100\ ft)^2$

$$= 0.785 \times 100\text{ ft} \times 100\text{ ft} = 7{,}850\text{ ft}^2$$

$$\frac{7{,}850\text{ ft}^2}{1} \times \frac{1\text{ gal}}{200\text{ ft}^2} = 39.25\text{ gal} = 40\text{ gal}$$