

PDH NOW

Principles of Water Treatment

PDH: 4.0 Hours

Dr. M. A. Karim, P.E., F.ASCE

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Principles of Water Treatment

1. Introduction

This course introduces the principles of water chemistry, physical, chemical, biological, and radiological characteristics of water, reaction kinetics, coagulation/flocculation, softening, mixing and flocculation, sedimentation, filtration, disinfection, adsorption, and water plant waste management. In this course we define several terms related to water supply systems, water supply systems classifications, chemical units, and discuss the water quality, water quality standards, working principles of coagulation/flocculation, softening, mixing and flocculation, sedimentation, filtration, disinfection, and adsorption. we solve some problems to understand the basic concept of water treatment and design some unit processes. This course is suggested for civil engineers, environmental engineers, and water and wastewater treatment plant managers and operators.

2. Learning Objectives

Upon successful completion of this course, the participants will be able to:

- explain the water chemistry.
- discuss the reaction kinetics, water quality, and water quality standards.
- describe the concepts of coagulation/ flocculation, water softening process, sedimentation, filtrations, and adsorption.
- design the unit processes for water treatment.

3. Definitions

Public Water System (PWS): Provide water for human consumption through pipes or other constructed conveyances to at least **15** service connections or serve an average of at least **25** people for at least **60** days in a year. EPA has defined 3 types of PWS:

Community Water System (CWS): A public water system that supplies water to the same population year-round.

Non-Transient Non-Community Water System (NTNCWS): A public water system that regularly supplies water to at least **25** of the same people at least **6** month per year, but not year-round. For instance, schools, hospitals, office, factories that have their own water system.

Transient Non-Community Water System (TNCWS): A public water system that supplies water in a place such as gas station or campground where people do not remain for long period of time.

EPA also classifies water systems according to the number of people they serve:

- Very small water systems – serve 25 – 500 people
 - Small water systems – serve 501 – 3,300 people
 - Medium water systems – serve 3,301 – 10,000 people
 - Large water systems – serve 10,001 – 100,000 people
 - Very large water systems – serve 100,000+ people
- Pathogen = An organism which causes disease
 - Potable = Safe to drink
 - Palatable = Pleasing to drink
 - Wholesome water → unpolluted, free from toxic substances as well as excessive amounts of mineral and organic matter that may impair the water quality
 - Why make water palatable? → To make the water pleasant to drink.

4. Chemical Units

Since solutes in solution are often analyzed by weight, the terms weight percent and milligram per liter (mg/L) are used.

In order to perform stoichiometric calculations, it is necessary to convert to common units, and the terms molarity and normality are used.

Weight percent, P specifies the grams of substance per 100 grams of solution and it expressed as

$$P = \frac{W}{W + W_0} \times 100\%$$

where, P = % of substance by weight,
 W = grams of substance (solute), and
 W_0 = grams of solvent

Parts per million (ppm): Sometimes chemical concentrations are reported in ppm. If the density of water is 1 g/ mL (1 gm/cc), then $1 \text{ mg/L} = 1 \text{ ppm}$.

$$\frac{1 \text{ mg}}{\text{L}} = \frac{1 \text{ mg}}{\text{L}} \times \frac{1 \text{ L}}{1,000 \text{ mL}} \times \frac{1 \text{ mL}}{1 \text{ gm}} \times \frac{1 \text{ gm}}{1,000 \text{ mg}} = \frac{1 \text{ mg}}{10^6 \text{ mg}} = 1 \text{ ppm}$$

If the same assumption is made, then the weight % of 1 mg/L can be determined as

$$P = \frac{W}{W + W_0} \times 100 = \frac{1 \text{ mg} \times 100}{1 \text{ L}} = \frac{10^{-3} \text{ g} \times 100}{1,000 \text{ g}} = 1 \times 10^{-4} \%$$

Which means, $1 \text{ mg/L} = 0.0001\%$ or $1\% = 10,000 \text{ mg/L}$

Molecular weight (MW): the relative weight of a mole of a substance. MW is the sum of the atomic weights.

Equivalent weight (EW): is the MW divided by the number (n) of electrons transfer in redox reactions or the number of protons transferred in acid/base reactions. $\underline{EW = MW/n}$

In an acid/base reaction, \underline{n} is the number of hydrogen ions that the molecule transfers. This is, an acid gives up an \underline{EW} of hydrogen ions, and base accepts an \underline{EW} of hydrogen ions.

In precipitation reaction, \underline{n} is the valance of the element in question.

For compounds, \underline{n} is equal to the number of hydrogen ions that would be required to replace the cation; that is for CaCO_3 it would take 2 hydrogen ions to replace calcium, therefore, $n = 2$.

In oxidation/reduction reactions, n is equal to the change in oxidation number that the compound undergoes in reaction.

Molecular Formulas	Molecular Weight	n	Equivalent Weight
		# Equiv per mole	
CO_3^{2-}	60.0	2	30.0
CO_2	44.0	2	22.0
Ca(OH)_2	74.1	2	37.1
CaCO_3	100.1	2	50.0
$\text{Ca(HCO}_3)_2$	162.1	2	81.1
CaSO_4	136.1	2	68.1
Ca^{2+}	40.1	2	20.0
H^+	1.0	1	1.0
HCO_3^-	61.0	1	61.0
$\text{Mg(HCO}_3)_2$	146.3	2	73.2
Mg(OH)_2	58.3	2	29.2
MgSO_4	120.4	2	60.2
Mg^{2+}	24.3	2	12.2
Na^+	23.0	1	23.0
Na_2CO_3	106.0	2	53.0
OH^-	17.0	1	17.0
SO_4^{2-}	96.1	2	48.0

Molarity (M): is the number of moles in a liter of solution. A 1-molar (**1 M**) solution has **1** mole of substance per liter of solution. Molarity is related to mg/L, as follows:

$$\text{mg/L} = \text{molarity} \times \text{molecular weight} \times 10^3 = (\text{moles/L}) \times (\text{g/moles}) \times (1,000 \text{ mg/g})$$

Normality (N): is the number of EW per liter of solution and it is related to molarity (*M*) by

$$N = Mn$$

5. Water Chemistry

Mainly chemical reactions related to water treatments. Fundamentals of water chemistry is necessary to understand the water quality monitoring, assessment, and treatment systems.

Physical Properties of Water such as *mass density* (ρ), *specific weight* (γ), *specific gravity* (*S*), *dynamic viscosity* (μ - FL^{-2}T), and *kinematic viscosity* (ν - L^2T^{-1}).

$$\nu = \frac{\mu}{\rho}$$

✓ Physical Properties of Water

- *mass density* (ρ) - Mass per unit volume, measured in units of kg/m^3 .
- *specific weight* (γ) - Force per unit volume, measured in units of kN/m^3
- *specific gravity* (*S*) - is given by $S = \rho/\rho_o = \gamma/\gamma_o$
- *dynamic viscosity or absolute viscosity* (μ) - has dimension of mass per unit length per time, with units of Pa.s
- *kinematic viscosity* (ν) = μ/ρ (m^2/s)
- *Viscosity is a measure of a fluid's resistance to flow. It describes the internal friction of a moving fluid. A fluid with large viscosity resists motion because its molecular makeup gives it a lot of internal friction. A fluid with low viscosity flows easily because its molecular makeup results in very little friction when it is in motion. Gases also have viscosity, although it is a little harder to notice it in ordinary circumstances*

✓ Chemical reactions - 4 types of reactions

- **precipitation**
 - ✓ solubility of complexes in water
- **acid/base**

- ✓ acid (low pH) releases protons, base (high pH) accepts protons.
- **ion-association**
 - ✓ dissolved ion can react with each other and form a solid compound or may exist in water complexed with other ions.
- **chemical reactions – oxidation/reduction**
 - ✓ **An** atom, molecule, or ion is said to undergo *oxidation* when it loses an electron, and to undergo *reduction* when it gains an electron.
 - ✓ **Oxidation-reduction** reactions occur between atoms to form molecules and ions with polar covalent bonds.
 - ✓ **An** oxidizing agent is any substance that can add electrons [e.g, O(O), Cl(O), Fe(III), Cr(IV), *Mn(IV)*, *N(III)*, *S(O)*, etc.]
 - ✓ **A** reducing agent is any substance that can give up electrons [e.g., H(O), Fe(O), Mg(O), Fe(II), Cr(II), *Mn(IV)*, *N(III)*, Cl(-I), *S(O)*, S(-II), S(IV), etc.]
 - ✓ **Mn(IV)**, **N(III)**, **S(O)** can act as both oxidizing and reducing agent under proper conditions.
- ✓ **Buffer Solutions:** A solution that resists large changes in pH when an acid or base is added or when the solution is diluted. A solution containing weak acid and its salt is an example of a buffer.
- ✓ **Alkalinity:** Alkalinity is defined as the sum of all titratable bases down to about pH 4.5. In most waters the only significant contributions to alkalinity are carbonate species and any free H⁺ and OH⁻. The H⁺ that can be taken up by a water containing primarily carbonate species is

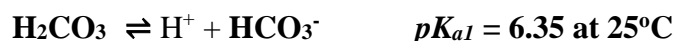
$$\text{Alkalinity} = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{OH}^-] - [\text{H}^+]$$

where [] refers to concentrations in mole/L.

- ✓ In most natural waters (pH 6 to 8), the OH⁻ and H⁺ are negligible, such that

$$\text{Alkalinity} = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}]$$

[CO₃²⁻] is multiplied by 2 because it can accept 2 protons. The pertinent acid/base reactions are:



where, $pK_a = -\log K_a$, and $K_a =$ equilibrium constant

- ✓ **Activity Coefficients:** For dilute solutions, the ions in solution can be considered to act independently from one another. As the concentration of ions in solution increases, the interaction of their electric charges affects their equilibrium relationship. This interaction is measured in terms of *ionic strength*. To account for high ionic strength, the equilibrium relationships are modified by incorporating *activity coefficients*. **Activity Coefficients** are symbolized by $\gamma(\text{ion})$. Activity is then the product of the molar concentration of the species and its activity coefficient. **For Example**, the solubility product of CaCO_3 would be

$$K_s = \{\gamma(\text{Ca}^{2+}) \times [\text{Ca}^{2+}]\} \{\gamma(\text{CO}_3) \times [\text{CO}_3]\}$$

6. Reaction Kinetics

The study of how the chemical reactions proceed with time is called reaction kinetics.

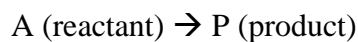
Rate of reaction - rate of formation and disappearance of a compound

Homogeneous reactions - take place in a single phase

Heterogeneous reactions - take place in multiple phases (solid, liquid, and gas)

- **Order of reaction** - sum of the exponents in the reaction rate equation.

1. **Zero-order kinetics** – reactions proceed at a rate independent of the concentration of any reactant or product; therefore, the disappearance of reactants and appearance of products are linear.



Using C to represent the concentration of A at any time t , the disappearance of A with respect to time is

$$\frac{dC}{dt} = kC^0 = -k$$

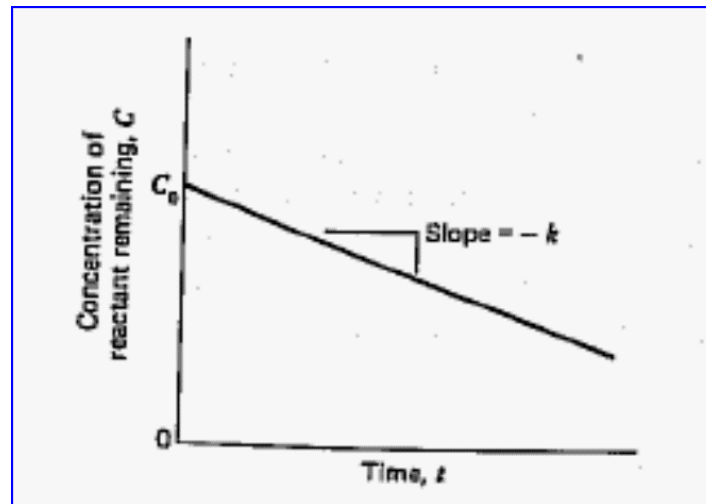
$\frac{dC}{dt}$ = rate of change in concentration of A with time where,

k = reaction-rate constant, per day

Integrating this equation and rearranging the terms,

$$C = C_0 - kt$$

where, C = concentration of A at any time t , mg/L; C_0 = initial concentration of A , mg/L



Zero-order kinetic reaction

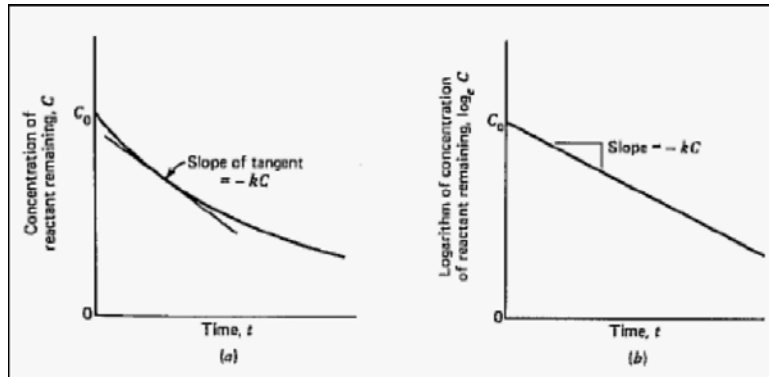
2. **First-order kinetics** – reactions proceed at a rate directly proportional to the concentration of one reactant. It represents a curve in normal graph paper, but linear to semi-log paper.

If it is considered that a single reactant converting to a single product ($A \rightarrow P$), the change in concentration C of A with respect to time is

$$\frac{dC}{dt} = -kC' = -kC$$

Integrating this equation and letting $C = C_0$ when $t = 0$, we get,

$$\ln \frac{C}{C_0} = -kt \quad \text{or} \quad C = C_0 e^{-kt}$$



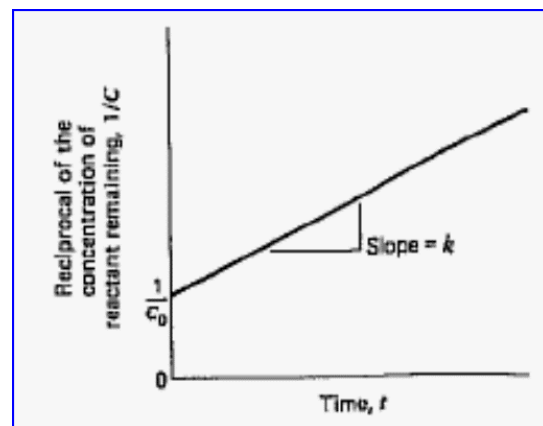
First-order kinetic reaction (a) normal (b) semi-log

3. **Second-order kinetics** - reactions proceed at a rate directly proportional to the second power of a single reactant being converted to a single product ($2A \rightarrow P$). The reaction rate is

$$\frac{dC}{dt} = -kC^2$$

Integrating this equation and letting $C = C_0$ when $t = 0$, we get,

$$\frac{1}{C} - \frac{1}{C_0} = kt$$



7. Water Quality

The following four categories such as physical, chemical, biological, and radiological characteristics/parameters, are used to describe water/wastewater quality:

Physical Characteristics/Parameters: Physical characteristics relate to the quality of water for domestic use and usually associated with the appearance of water such as:

- **pH**
 - ✓ In chemistry, **pH** is a scale used to specify how acidic or basic a water-based solution is. Acidic solutions have a lower pH, while basic solutions have a higher pH. At room temperature (25 °C), pure water is neither acidic nor basic and has a pH of 7.
 - ✓ The concept of pH was first introduced by the Danish chemist Søren Peder Lauritz Sørensen at the [Carlsberg Laboratory](#) in 1909 and revised to the modern pH in 1924 to

accommodate definitions and measurements in terms of electrochemical cells. In the first papers, the notation had the "H" as a subscript to the lowercase "p", as so: p_H .

- ✓ The exact meaning of the "p" in "pH" is disputed, but according to the Carlsberg Foundation, pH stands for "[power](#) of hydrogen". It has also been suggested that the "p" stands for the [German](#) *Potenz* (meaning "power"), others refer to [French](#) *puissance* (also meaning "power", based on the fact that the Carlsberg Laboratory was French-speaking). Another suggestion is that the "p" stands for the [Latin terms](#) *pondus hydrogenii* (quantity of hydrogen), *potentia hydrogenii* (capacity of hydrogen), or potential hydrogen. It is also suggested that Sørensen used the letters "p" and "q" (commonly paired letters in mathematics) simply to label the test solution (p) and the reference solution (q). Currently in [chemistry](#), the p stands for "decimal [cologarithm](#) of", and is also used in the term pK_a , used for [acid dissociation constants](#).
- **Color**
 - ✓ Source: Domestic and industrial wastes, natural decay of organic materials.
 - ✓ Fresh wastewater → light brownish gray; with time → dark gray; more time → black (septic). Sometimes pink due to algae or due to industrial colors.
- **Turbidity**
 - ✓ **Turbidity** is the cloudiness or [haziness](#) of a [fluid](#) caused by large numbers of individual [particles](#) that are generally invisible to the [naked eye](#), similar to [smoke in air](#). The measurement of turbidity is a key test of [water quality](#).
 - ✓ [Fluids](#) can contain suspended solid matter consisting of particles of many different sizes. While some suspended material will be large enough and heavy enough to settle rapidly to the bottom of the container if a liquid sample is left to stand (the [settable solids](#)), very small particles will settle only very slowly or not at all if the sample is regularly agitated or the particles are [colloidal](#). These small solid particles cause the liquid to appear turbid.
 - ✓ **Turbidity** (or haze) is also applied to transparent solids such as glass or plastic. In plastic production, haze is defined as the percentage of light that is deflected more than 2.5° from the incoming light direction.
- **Taste and Odor**
 - ✓ Source: Decomposing wastewater, industrial wastes.
 - ✓ Odor is produced by gas production due to the decomposition of organic matter or by substances added to the wastewater.
 - ✓ Detection of odor: Odor is measured by special instruments such as the Portable H_2S meter which is used for measuring the concentration of hydrogen sulfide.
- **Solids**
 - ✓ Source: Domestic water supply, domestic and industrial wastes, soil erosion, inflow infiltration.
 - ✓ Solids are classified into three main types:
 - Total Solids (TS): All the matter that remains as residue upon evaporation at $103^\circ C$ to $105^\circ C$.

- Total Settleable solids or suspended solids (TSS): Settleable solids or suspended solids are measured in mg/L, which is an approximate measure of the sludge that can be removed by primary sedimentation.
- Total dissolved solids (TDS) or Filterable solids (FS).
- **Temperature**
 - ✓ Source: Domestic and industrial wastes.
 - ✓ Temperature of wastewater is commonly higher than that of water supply. Depending on the geographic location the mean annual temperature varies in the range of 10 to 21°C with an average of 16°C.
 - ✓ Importance of temperature:
 - Affects chemical reactions during the wastewater treatment process. Affects aquatic life (Fish,).
 - Oxygen solubility is less in warm water than cold water.
 - Optimum temperature for bacterial activity is in the range of 25°C to 35°C.
 - Aerobic digestion and nitrification stop when the temperature rises to 50°C. When the temperature drops to about 15°C, methane producing bacteria become inactive.
 - Nitrifying bacteria stop activity at about 5°C.

Chemical Characteristics/Parameters: Chemical characteristics of waters are sometimes evidenced by their observed reactions. The following are the parts of chemical characteristics of water.

- Chloride
- Fluorides
- Metals (Iron, Lead, Manganese, Sodium, and Zinc)
- Sulfate
- Carbon dioxide
- Alkalinity
- Hardness
- Total solids, dissolved solids, suspended solid
- Toxic organic substances – 120 toxic organic substances that include pesticides, insecticides and solvents.
- Toxic inorganic substances (Nitrates, cyanides, and heavy metals)

Microbiological Characteristics - Pathogens (disease producing organisms) that include viruses, bacteria, protozoa, and helminths (worms).

- Total Coliform - The most widely used test estimates the number of microorganisms of the coliform group.
- This grouping includes two genera: Escherichia coli (E-coli) and Aerobacter aerogenes.
- **Why coliforms were selected as an indicator organism?**
 - ✓ Common inhabitants of intestinal tract

- ✓ Excreted in large quantities
- ✓ Can survive in water
- ✓ Are relatively easy to culture

Radiological Characteristics

- The effects of human exposure to radiation or radioactive materials are harmful, and unnecessary exposure should be avoided. Human have always been exposed to natural radiation from water, food, and air.
- The amount of radiation to which the individual is normally exposed varies with the amount of background radioactivity.
- Water with high radioactivity is not normal and is confined in great degree to areas where nuclear industries are situated.

8. Water Quality Standards

President Ford signed the National Safe Drinking Water Act (SDWA) into law on December 16, 1974. EPA was directed to establish maximum contaminant levels (MCLs) for public water systems to prevent the occurrence of any known or anticipated adverse health effects with an adequate margin of safety.

- ✓ **Secondary Maximum Contaminant Levels (SMCLs):** The National SDWA provided additional set of standards to prescribe maximum limits for those contaminants that tend to make water disagreeable to use, but do not have any particular adverse health effect.
- ✓ **American Water Works Association (AWWA) Goals:** The primary and secondary maximum contaminant levels are the maximum allowed. However, reasonable goal (desirable limits) may be much lower than MCLs themselves.

Types of Water Quality Standards: The water quality stands are set for

- Physical Characteristics
- Chemical Characteristics
- Biological Characteristics
- Radiological Characteristics

9. Water Classification and Treatment Systems

Classification by source

- ✓ **Surface water** - contaminated with bacteria, viruses or inorganic substances which could present a health hazard.

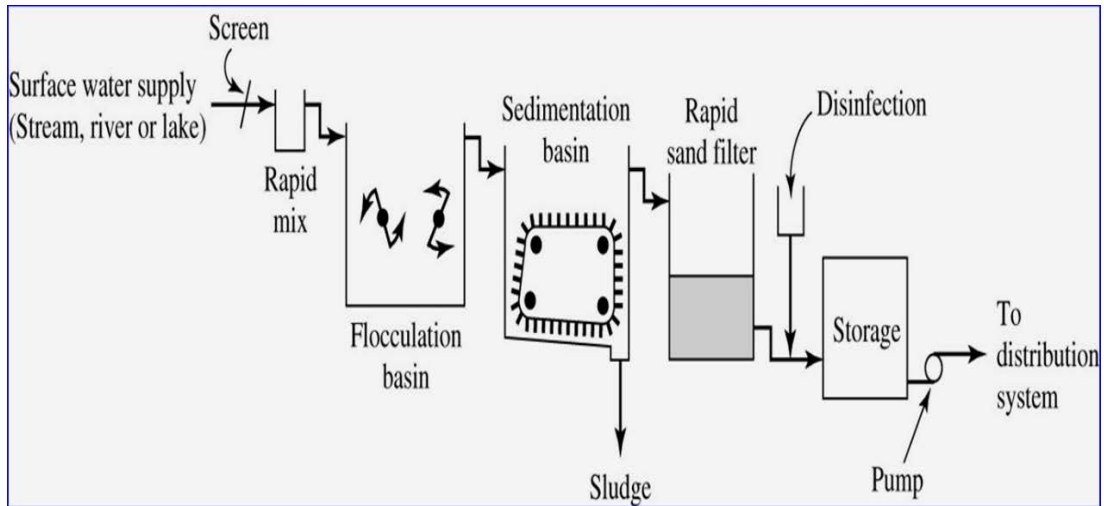
- ✓ **Groundwater** - may contain in high concentrations of calcium, iron, manganese, and magnesium - further classified as to its source - deep or shallow wells.

- **Treatment Systems**

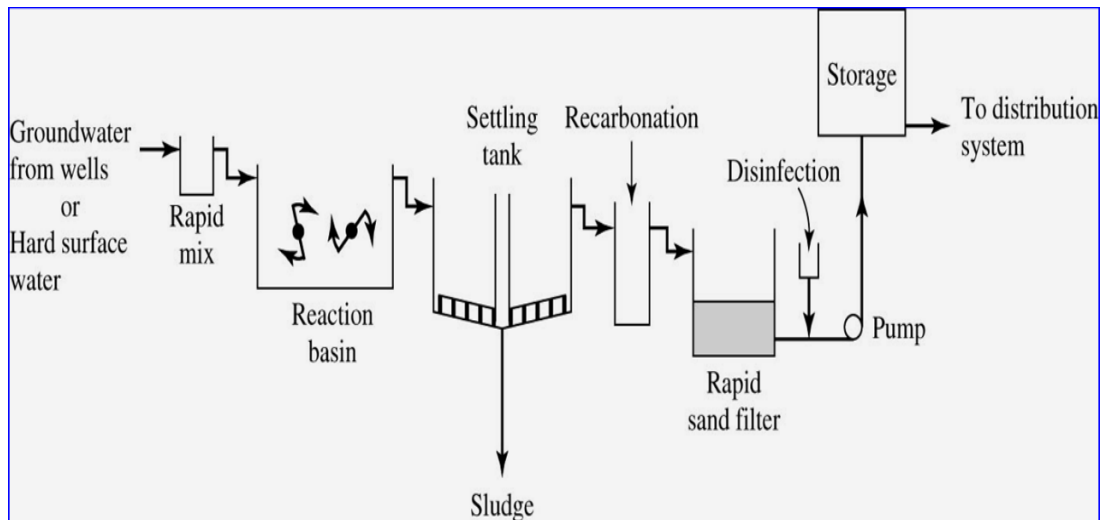
Pollutant Type	Parameter to measure in the Lab	Treatment Process/Technology
Suspended/colloidal solids	Turbidity, Color, TS, TSS	Coagulation/Flocculation, sedimentation, filtration
Dissolved solids	pH, Color, TDS, Hardness, Alkalinity, Metals, THM etc.	Chemical precipitation, Softening, Absorption, Adsorption
Suspended/Dissolved solids	Nutrients - Nitrogen, Phosphorus	Chemical precipitation, Biological treatment
	Organics – BOD ₅ , COD	Chemical and Biological treatment
Microorganisms/pathogens	E-coli, Total coliform, Fecal coliform, Salmonella, and other pathogens	Disinfection (by Chlorine, Ozone, UV rays)

- Treatment systems can be classified as simple disinfection, filtration plants, or softening plants.
 - Plants employing simple chlorination have a high water quality source and chlorinate to ensure that the water reaching customers contains safe bacteria levels.
 - Generally, filtration plant is used to treat **surface water** and a softening plant to treat **groundwater**.
 - **Filtration Plant** --> rapid mixing, flocculation, sedimentation, filtration, and disinfection are employed to remove color, turbidity, taste and odors, and bacteria. Additional operations may include bar racks or coarse screens if floating debris and fish are a problem.
 - **Softening plants** --> utilize the same unit operations as filtration plants but use different chemicals. *The primary function of a softening plant is to remove hardness (calcium and magnesium).* Chemical doses are higher in softening, and the corresponding sludge production is greater.

- **Treatment Systems-flow diagrams**



Flow diagram for conventional surface water treatment plant (filtration plant)



Flow diagram for water (mostly groundwater) softening plant

10. Coagulation/Flocculation

The objective of coagulation (and subsequently flocculation) is to turn the small particles of color, turbidity and bacteria into larger flocs, either as precipitates or suspended particles. **Coagulation** applies to the removal of colloidal particles. **Coagulation** is a method to alter the colloids so that they will be able to approach and adhere to each other to form larger **floc** particles.

- Coagulation = Charge reduction
- Flocculation = Contact of particles

- Alkalinity in Coagulation - Needed to neutralize acid formed

During coagulation a +ve ion is added to water to reduce the surface charge to a point where the colloids are not repelled from each other. A **coagulant** is a substance (chemical) that is added to the water to accomplish coagulation.

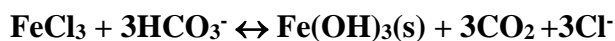
- Three key properties of coagulant:
 - ✓ Trivalent cation
 - ✓ Nontoxic
 - ✓ Insoluble in neutral pH range
- **The** most commonly used coagulants are aluminum (Al^{3+}) and ferric iron (Fe^{3+}). Both of them meet the key requirements.
- **Alum:** dry or liquid alum [$\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$]. **Reaction** with water containing alkalinity



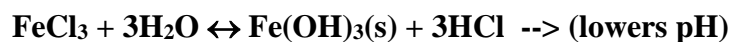
Reaction with water containing insufficient alkalinity



- **Iron:** Iron can be purchased as either the sulfate salt [$\text{Fe}_2(\text{SO}_4)_3 \cdot x\text{H}_2\text{O}$] or the chloride salt ($\text{FeCl}_3 \cdot x\text{H}_2\text{O}$). **Reaction** of FeCl_3 with water containing alkalinity



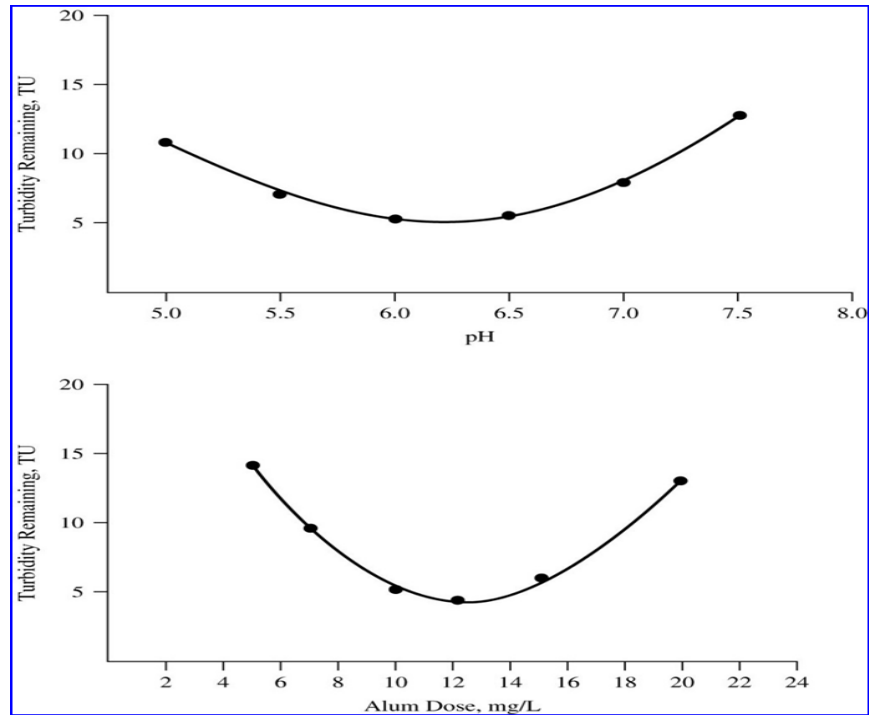
Reaction with water containing insufficient alkalinity



- **Coagulant aids:** pH adjusters, activated silica, clay, and polymers.

Alum Coagulation

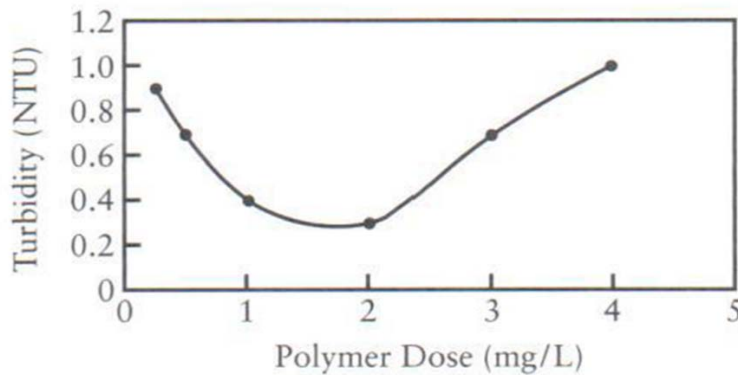
results from jar test



Example 1: Given the following jar test results, what is the optimum dose for polymer that should be used in the treatment process?

Container No.	1	2	3	4	5	6
Alum (mg/L)	6	6	6	6	6	6
Polymer (mg/L)	0.25	0.5	1.0	2.0	3.0	4.0
Turbidity (NTU)	0.9	0.7	0.4	0.3	0.7	1.0

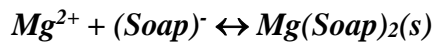
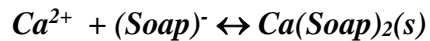
Solutions: Plotting Polymer dose vs. Turbidity



Lowest turbidity is obtained when polymer dose is about 2 mg/L. Actually, it is between 1 and 2 mg/L. It's better to use 2 mg/L.

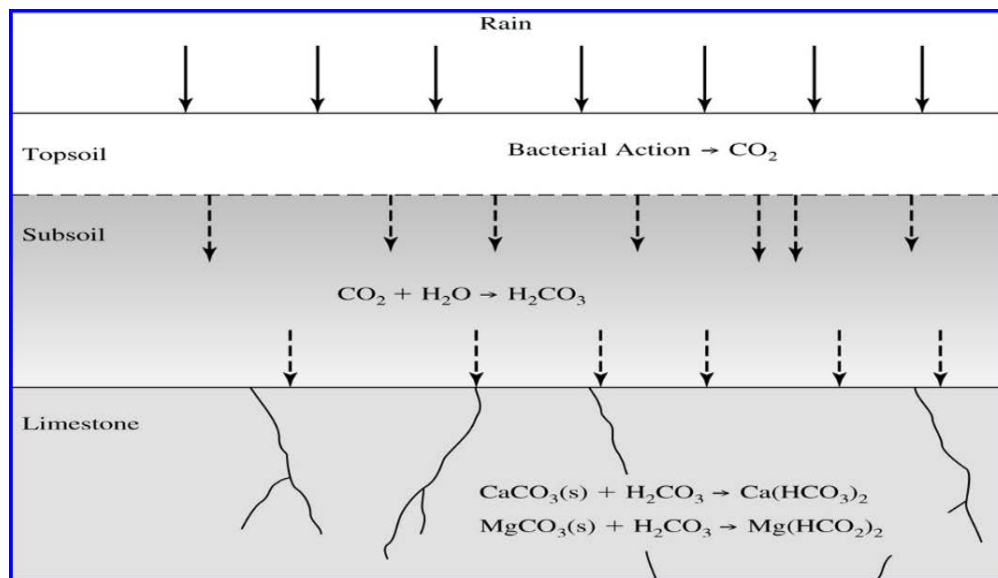
11. Softening

As mentioned earlier that softening is employed to groundwater source for removing hardness. The term hardness is used to characterize a water that does not lather well, cause a scum in the bathtub and leaves hard, white, crusty deposits (scale) on coffee pots, tea kettles, and hot water heaters. **Failure** to lather well and the formation of scum on bathtubs is the result of the reactions of *Ca* and *Mg* with soap.



Soaps:

- Soaps are the sodium and potassium salts of long chain carboxylic acid. A soap molecule consists of a long hydrocarbon chain (composed of carbon and hydrogen) with a carboxylic acid one end which is ionic bonded to metal ion usually sodium or potassium.
- A soap has a large non-ionic hydrocarbon group and an ionic group $COO-NA^+$.
- **Hardness** is defined as the sum of all polyvalent cations. The common unit is mg/L as $CaCO_3$. **Hardness** > 150 mg/L as $CaCO_3$ is objectionable.
 - ✓ **Common** water treatment goal: 75 - 120 mg/L as $CaCO_3$.
- **Natural process by which water becomes hard:**
 - ✓ Rainwater enters the topsoil (respiration of microorganisms increases CO_2),
Bacterial Action $\rightarrow CO_2$
 - ✓ Subsoil: $CO_2 + H_2O \rightarrow H_2CO_3$
 - ✓ Limestone, $CaCO_3(s) + H_2CO_3 \rightarrow Ca(HCO_3)_2$
 - ✓ Limestone, $MgCO_3(s) + H_2CO_3 \rightarrow Mg(HCO_3)_2$



✓ $CaSO_4$ (gypsum) and $MgSO_4$ also contribute to the hardness.

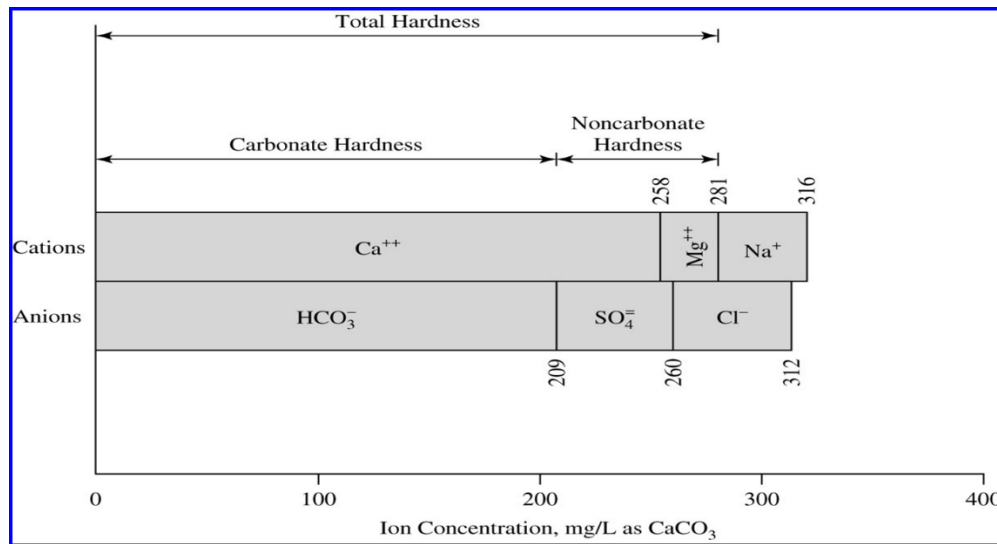
Since Ca and Mg predominate, it is often convenient in performing softening calculations to define the **total hardness (TH)** of a water as the sum of these elements.

$$TH = Ca^{2+} + Mg^{2+}$$

Total hardness is also defined as $TH = CH + NCH$

$CH =$ carbonate hardness associated with HCO_3^-

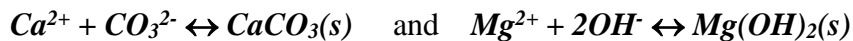
$NCH =$ non-carbonate hardness associated with other anions.



Bar graph of groundwater constituents

9.1 Lime-Soda SOFTENING

In Lime-Soda ($CaO-Na_2CO_3$) softening, it is possible to calculate the chemical doses necessary to remove hardness. Hardness precipitation is based on the following two solubility reactions:



The objective is to precipitate the Ca as $CaCO_3$ and the Mg as $Mg(OH)_2$. In order to precipitate Ca , the pH→10.3 and Mg , the pH→11.0

- **Softening Chemistry:**

- ✓ The chemical processes used to soften water are a direct application of the law of mass action.
- ✓ Concentration of CO_3^{2-} and/or OH^- are increased by addition of chemicals and drive the solubility reactions to the right.

- ✓ The process converts the naturally occurring bicarbonate alkalinity (HCO_3^-) to carbonate (CO_3^{2-}) by addition of hydroxyl ions.
- ✓ OH^- ions cause the carbonate buffer system to shift to the right hand, thus provide the carbonate for precipitation reaction.
- ✓ The common source of OH^- ions is $\text{Ca}(\text{OH})_2$.
- ✓ CaO (quicklime) + $\text{H}_2\text{O} \leftrightarrow \text{Ca}(\text{OH})_2$ (hydrated lime) + Heat (exothermic)
- ✓ Conversion process is called slaking.
- ✓ When carbonate ions (CO_3^{2-}) must be supplied, the most common chemical chosen is sodium carbonate (Na_2CO_3). Sodium carbonate is commonly referred as *soda ash* or *soda*.
- ✓ The reactions are regulated by controlling pH. First, any free acids are neutralized. Then pH is raised to precipitate the CaCO_3 ; if necessary, the pH is raised further to remove $\text{Mg}(\text{OH})_2$. Finally, if necessary, CO_3^{2-} is added to precipitate the noncarbonate hardness.

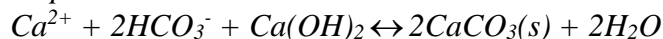
▪ **Five process with six reactions:**

1. Neutralization of carbonic acid (H_2CO_3)

$\text{CO}_2 + \text{Ca}(\text{OH})_2 \leftrightarrow \text{CaCO}_3(\text{s}) + \text{H}_2\text{O} \rightarrow$ no hardness is removed in this step, just neutralization in order to raise pH

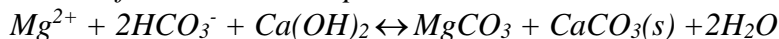
2. Precipitation of carbonate hardness due to calcium:

To raise the pH to about 10.3 to precipitate calcium carbonate. To achieve this pH, all the bicarbonate is converted to carbonate. The carbonate then serves as the common ion for the precipitation reaction.

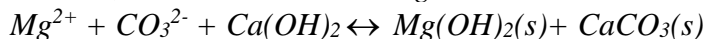


3. Precipitation of carbonate hardness due to magnesium:

To remove carbonate hardness that results from the presence of Mg, more lime needs to be added to achieve a pH of about 11.0. The reaction occurs in two stages. The 1st stage occurs when all of the HCO_3^- in step 2 above is converted.

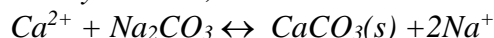


The hardness of the water did not change because MgCO_3 is soluble. With the addition of more lime, the hardness due to Mg is removed.



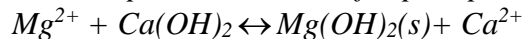
4. Removal of noncarbonate hardness due to calcium:

In order to remove noncarbonate hardness due to calcium, no further increase in pH is necessary. Instead, additional carbonate in the form of soda ash (Na_2CO_3) is necessary.

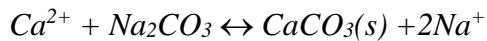


5. Removal of noncarbonate hardness due to magnesium:

In order to remove noncarbonate hardness due to magnesium, both lime and soda need to be added. The lime provides the OH⁻ for precipitation of the magnesium.



Although Mg is removed, there is no change in hardness since the Ca is still in solution. To remove the Ca, soda must be added.



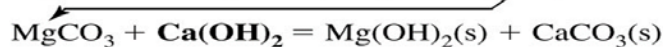
This is the same reaction that is used to remove noncarbonate hardness due to calcium

- **Summary of Softening Reactions:**

Neutralization of Carbonic Acid



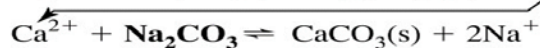
Precipitation of Carbonate Hardness



Precipitation of Noncarbonate Hardness Due to Calcium



Precipitation of Noncarbonate Hardness Due to Magnesium



- **Process limitation and empirical considerations:**

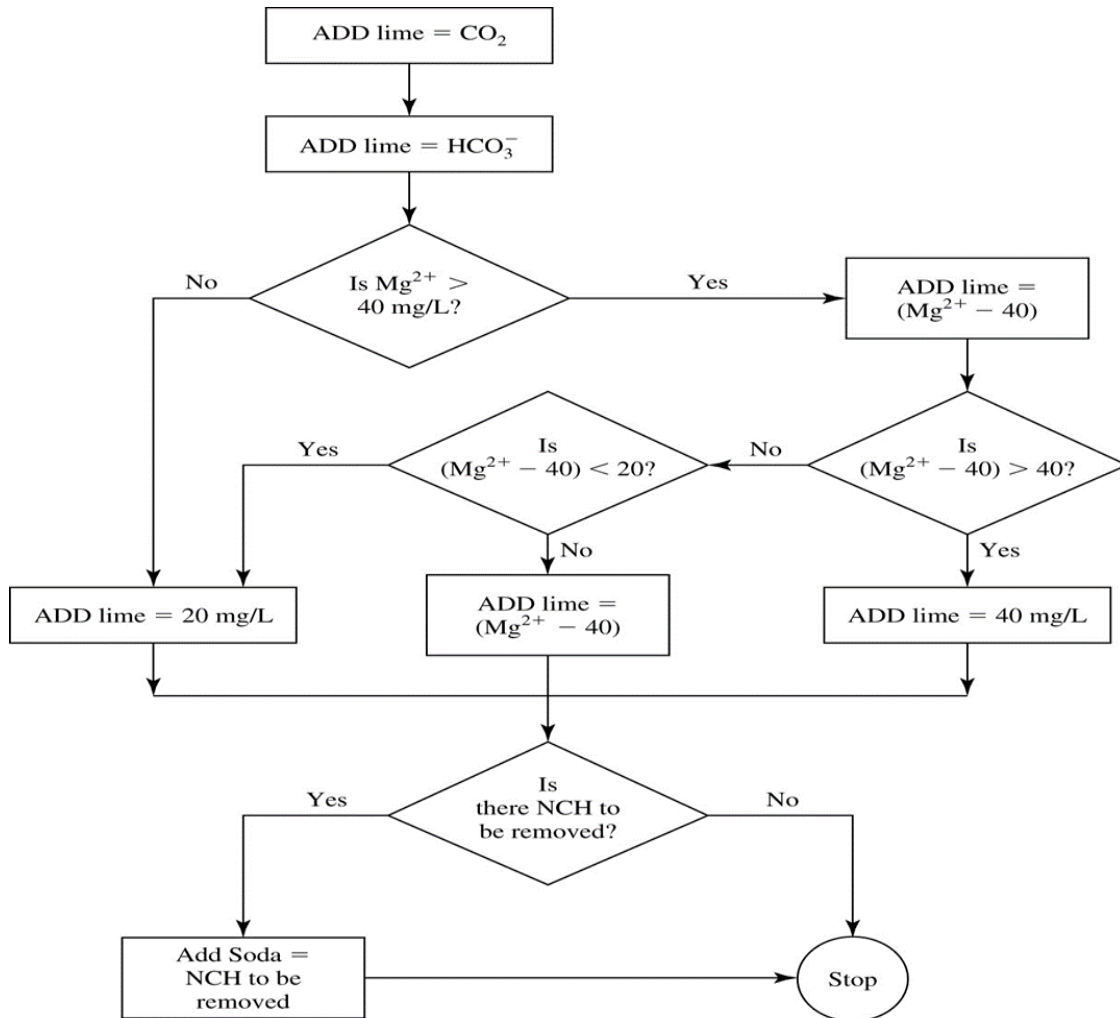
- ✓ Lime-soda softening cannot produce a water completely free of hardness because of the solubility of CaCO_3 and $\text{Mg}(\text{OH})_2$, the physical limitations of mixing and contact, and the lack of sufficient time for reactions to go to completion.
- ✓ Minimum Ca hardness that can be achieved = 30 mg/L as CaCO_3
- ✓ Minimum Mg hardness that can be achieved = 10 mg/L as CaCO_3
- ✓ Final hardness is targeted = 75 - 120 mg/L as CaCO_3

In order to achieve reasonable removal of hardness in a reasonable time, minimum excess of 20 mg/L of $\text{Ca}(\text{OH})_2$ expressed as CaCO_3 must be provided.

- ✓ Mg in excess of 40 mg/L as CaCO_3 forms scales on heat exchange elements.
- ✓ Due to expense, Mg is removed which is in excess of 40 mg/L as CaCO_3
- ✓ Mg removal less than 20 mg/L as CaCO_3 , the basic excess of lime mentioned earlier is sufficient to ensure good results.
- ✓ For Mg removal in between 20 and 40 mg/L as CaCO_3 an excess lime equal to the Mg to be removed must be added.
- ✓ For Mg removal > 40 mg/L as CaCO_3 , excess lime of 40 mg/L as CaCO_3 must be added.
- ✓ Addition of excess lime > 40 mg/L as CaCO_3 does not appreciably improve the reaction kinetics.

- Chemical additions (as $CaCO_3$) to soften water may be summarized as follows:

Step	Chemical addition	Reason
Carbonate hardness		
1.	Lime = CO_2	Destroy H_2CO_3
2.	Lime = HCO_3^-	Raise pH ; Convert HCO_3^- to CO_3^{2-}
3.	Lime = Mg^{2+} to be removed	Raise pH ; precipitate $Mg(OH)_2$
4.	Lime = required excess	Drive reaction
Noncarbonate hardness		
5.	Soda = noncarbonate hardness to be removed	Provide CO_3^{2-}



Flow diagram for solving softening problems¹

- Unit conversion into mg/L as $CaCO_3$:

$$\text{mg/L as } CaCO_3 = (\text{mg/L as } \left(\frac{EW_{CaCO_3}}{EW_{species}} \right) \text{ species})$$

where,

EW (equivalent weight) = Atomic or molecular weight / $n = MW/n$

n = valence of the element in question and it is equal to the number hydrogen ions that would be required to replace the cation; that is, for $CaCO_3$ it would take 2 hydrogen ions to replace the calcium, therefore, $n = 2$. The units of EW are grams/equivalent (g/eq) or milligrams/milliequivalent (mg/meq).

Example 2: Convert the following ion concentrations into mg/L as $CaCO_3$. $Ca^{2+} = 103$ mg/L; $Mg^{2+} = 5.5$ mg/L; $Na^+ = 16$ mg/L; $HCO_3^- = 255$ mg/L; and $Cl^- = 37$ mg/L.

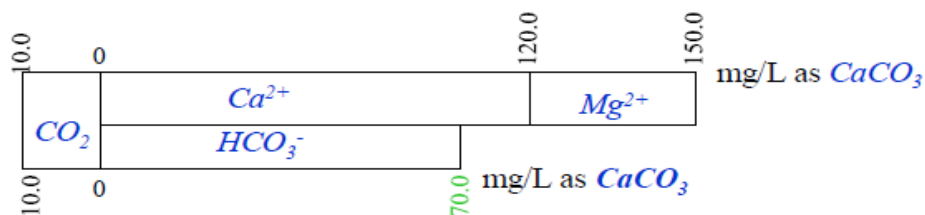
Solution:

Ion	mg/L as ion	EW of $CaCO_3$	MW of ion	Valence (n)	EW of ion	EW of $CaCO_3$ / EW of ion	mg/L as $CaCO_3$
Ca^{2+}	103	50	40	2	20	2.50	258
Mg^{2+}	5.5	50	24	2	12	4.17	23
Na^+	16	50	22.98	1	22.98	2.18	35
HCO_3^-	255	50	61	1	61	0.82	209
Cl^-	37	50	35.45	1	35.45	1.41	52

Molecular weight (MW) of $Ca = 40$ g; $C = 12$ g, $O = 16$ g; Valence of Ca , $n = 2$
 Therefore, MW of $CaCO_3 = 40+12+16 \times 3 = 100$ g; EW of $CaCO_3 = 100/2 = 50$ g/eq.

Example 3: Determine the lime and soda ash dose, in mg/L as $CaCO_3$, to soften the following water to a final hardness of **78.0** mg/L as $CaCO_3$. The ion concentrations reported below are all mg/L as $CaCO_3$. $Ca^{2+} = 120.00$; $Mg^{2+} = 30.0$; $HCO_3^- = 70.0$; and $CO_2 = 10.0$

Solutions:



CO_2 does not contribute to hardness; total hardness (TH) = 120.0 + 30.0 = 150 mg/L as $CaCO_3$. CH = 70.0 mg/L as $CaCO_3$.

$NCH_i = TH - CH = 150.0 - 70.0 = 80.0$ mg/L as $CaCO_3$.

Determination of the lime dose using Flowchart.

Step	Dose (mg/L as $CaCO_3$)
Lime = CO_2	10.0
Lime = HCO_3^-	70.0
Lime = $Mg^{2+} - 40 = -10$	0.0
<u>Lime = excess</u>	<u>20.0</u>
Total Lime	100.0

Is $Mg^{2+} > 40$, No
Add lime = 20 mg/L

The amount of lime to add is 100.0 mg/L as $CaCO_3$. = $100 \times (28/50) = 56$ mg/L as CaO = $56 \times (1.05) = 58.8$ mg/L as CaO with 5% impurities in lime. **Ans.**

EW of CaO = $56/2 = 28$.

The amount of NCH that can be left (NCH_f)

= 78.0 (final hardness in water) - 40.0 = 38.0 mg/L as $CaCO_3$.

NCH that must be removed, $NCH_r = NCH_i - NCH_f$

= 80.0 - 38.0 = 42.0 mg/L as $CaCO_3$.

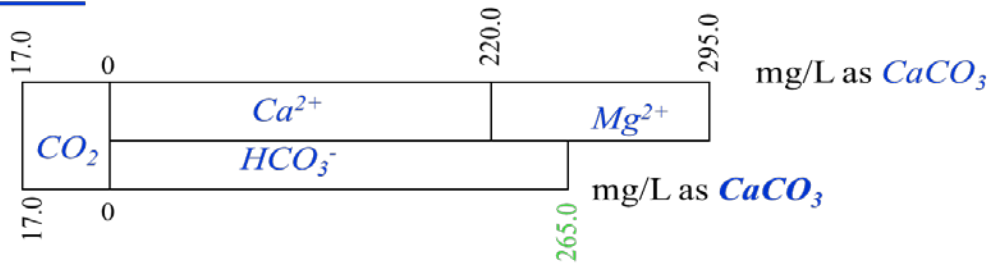
Thus, the amount of soda (Na_2CO_3) to be added

= 42.0 mg/L as $CaCO_3$. **Ans.**

= $42.0 \times (53/50) = 44.5$ mg/L as Na_2CO_3 = $44.5 \times (1.03) = 45.8$ mg/L as Na_2CO_3 with 3% impurities. EW of $Na_2CO_3 = 106/2 = 53$.

Example 4: Determine the lime and soda ash dose, in mg/L as CaCO_3 , to soften the following water to a final hardness of **70.0** mg/L as CaCO_3 . The ion concentrations reported below are all mg/L as CaCO_3 . $\text{Ca}^{2+} = 220.00$; $\text{Mg}^{2+} = 75.0$; $\text{HCO}_3^- = 265.0$; and $\text{CO}_2 = 17.0$

Solutions:



- CO_2 does not contribute to hardness; total hardness (TH) = $220.0 + 75.0 = 295.0$ mg/L as CaCO_3 . CH = 265.0 mg/L as CaCO_3 .
- $\text{NCH}_i = \text{TH} - \text{CH} = 295.0 - 265.0 = 30.0$ mg/L as CaCO_3 .

Determination of the lime dose using Flowchart.

Step	Dose (mg/L as CaCO_3)	
Lime = CO_2	17.0	Is $\text{Mg}^{2+} > 40$, Yes Add lime = $\text{Mg}^{2+} - 40 = 35$ mg/L Is $\text{Mg}^{2+} - 40 > 40$, No Is $\text{Mg}^{2+} - 40 < 20$, No Add lime = $\text{Mg}^{2+} - 40 = 35$ mg/L
Lime = HCO_3^-	265.0	
Lime = $\text{Mg}^{2+} - 40 = 35$	35.0	
Lime = excess	35.0	
Total Lime	352.0	

The amount of lime to add is 352.0 mg/L as $\text{CaCO}_3 = 352 \times (28/50) = 197.12$ mg/L as CaO = $197.12 \times (1.04) = 205$ mg/L as CaO with 4% impurities in lime. **Ans.**

$\text{EW of CaO} = 56/2 = 28.$

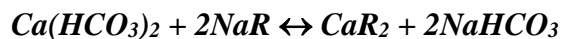
The amount of NCH that can be left (NCH_f)
 = **70.0** (final hardness in in water) - **40.0** = **30.0** mg/L as CaCO_3 .

NCH that must be removed, $\text{NCH}_r = \text{NCH}_i - \text{NCH}_f =$
30.0 - **30.0** = **0.0** mg/L as CaCO_3 .

Thus, add no soda (Na_2CO_3).

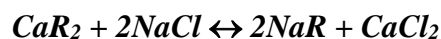
9.2 Ion-Exchange SOFTENING

Ion exchange can be defined as the reversible interchange of ions between a solid and a liquid phase in which there is no permanent change in the structure of solid. Typically, in water softening by ion exchange, the water containing hardness is passed through a column containing the ion exchange material. The hardness in the water exchanges with an ion from the ion-exchange material. Generally, the ion exchanged with hardness is sodium, as shown below:



Where **R** is the solid ion-exchange material.

When the ion-exchange material becomes saturated, no hardness will be removed. At this point **breakthrough** is said to have occurred. Ion-exchange material is regenerated. That is, the hardness is removed from the material by passing water containing large amount of Na^+ through the column. The mass action of having so much Na^+ in the water causes the hardness of the ion-exchange material to enter the water and exchange the sodium as follows:



The ion-exchange material can either be naturally occurring clays, called **zeolites**, or synthetically made resins. Softening industries use a unit called grains of hardness per gallon of water (gr/gal). $1\ gr/gal = 17.1\ mg/L$.

12. Reactors

The tanks used to perform physical, chemical, and biochemical reactions are called reactors. The reactors are classified based on their flow characteristics and their mixing conditions. **Batch Reactors:** *fill-and-draw type*: materials are added to the tank, mixed for sufficient time to allow the reaction to occur, and then drained. **Flow Reactors:** *continuous type of operation*: materials flow into, through, and out of the reactor at all times. Flow reactors are further classified as Completely Stirred Tank Reactor (**CSTR**):

CSTR: It is also called completely mixed flow reactor (**CMFR**): Uniform mixing throughout the tank. If the mass input rate into tank remains constant, the composition of the effluent remains constant.

Plug-flow reactors: fluid particles pass through the tank in sequence. Those that enter first leave the tank first.

Detention time or Retention time: The time that a fluid particle remains in the reactor. It is defined as:

$$t_o = \frac{V}{Q}$$

where, t_o = theoretical detention time, s

V = Volume of fluid in basin, m^3

Q = flow rate into basin, m^3/s .

- Reactor Design:
 - Mass-balance approach is used to design an ideal reactor and to approximate the design of real reactor.

Accumulation rate = Input Rate - Output Rate \pm Transformation rate.

- For batch reactor, Input = Output = 0
- The equation for batch reactor is

Accumulation rate = Transformation rate.

13. Mixing and Flocculation

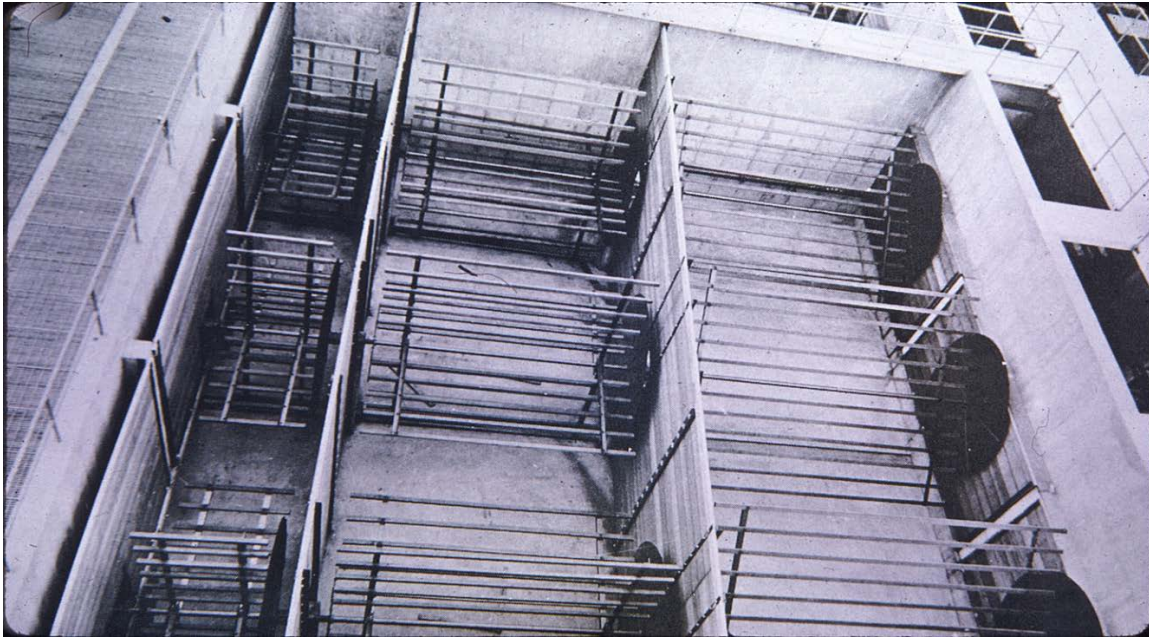
Chemical must be mixed with water if chemical reactions in **coagulating and softening a water going to take place**.

During **coagulation** and softening the chemical reactions that take place in rapid mixing form precipitates. Either **aluminum hydroxide or iron hydroxide** form during coagulation, while **calcium carbonate and magnesium hydroxide form during softening**.

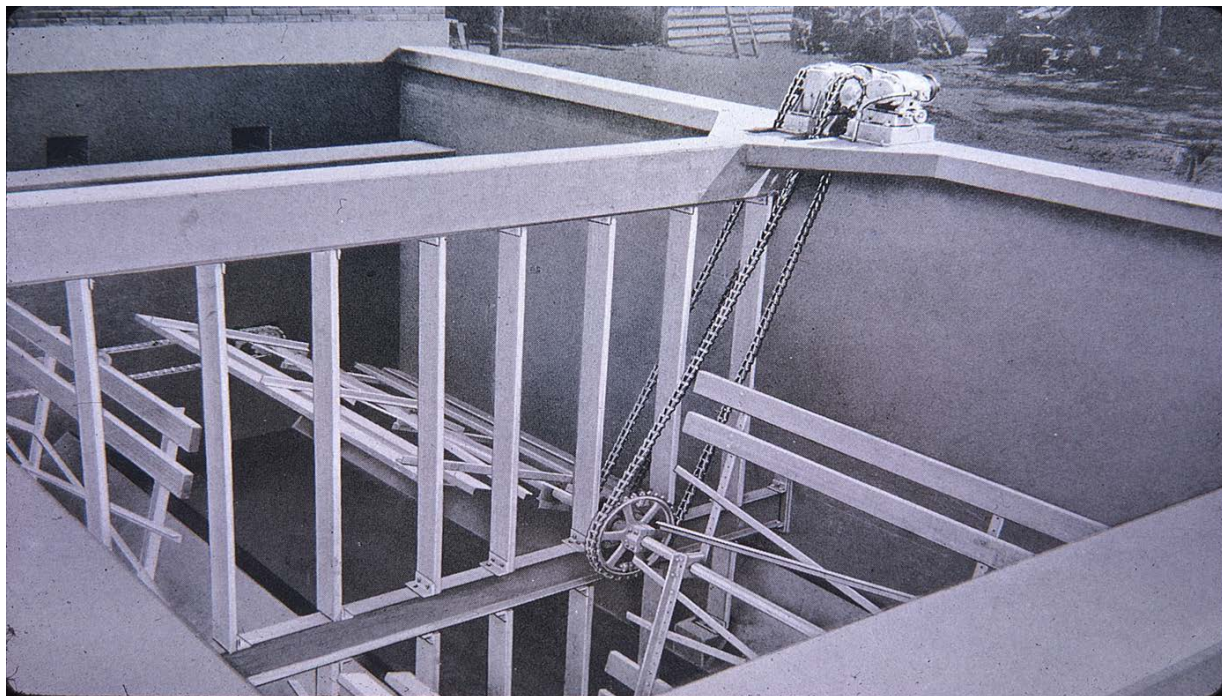
The precipitate formed in these processes must brought in contact with one another so that they agglomerate and form larger particles, called **flocs**.

This contacting process is called **flocculation** and is accomplished by slow, gentle mixing.

- **Coagulation = Charge reduction**
- **Flocculation = Contact of particles**



Paddle Mixers in Left Chamber and Flocculators in Right Two Chambers



Paddle Mixers Details

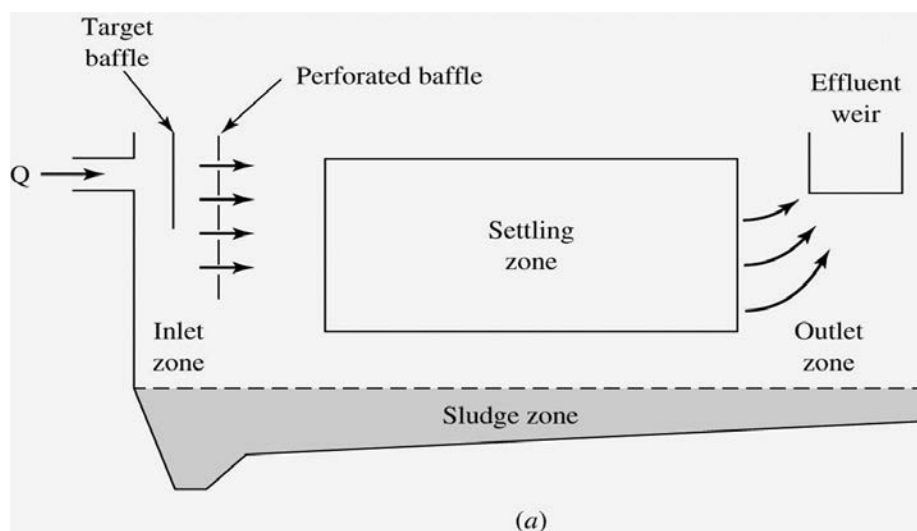
14. Sedimentation

Particles that will settle within a reasonable period of time can be removed in a sedimentation basin (also called clarifier).

Sedimentation basins are usually rectangular or circular with either radial or upward water flow pattern.

Regardless of the type of basin, the design can be divided into four zones: *Inlet*, *Settling*, *Outlet*, and *Sludge storage*.

The purpose of the **inlet zone** is to evenly distribute the flow and suspended particles across the x-section of the settling zone. Inlet zone is consists of a series of inlet pipes and baffles placed about **1 m** into the tank and extending the full depth of the tank.



Zones of sedimentation on a horizontal flow clarifier

- **Settling zone** is to facilitate the settling process. In an accurate design, the inlet and settling zones are each designed separately, and their lengths added together.
- The **outlet zone** is designed so as to remove the settled water from the basin without carrying away any of the floc particles.
- A fundamental property of water is that the velocity of flowing water is proportional to the rate divided by the area through which the water flows, that is

$$v = \frac{Q}{A_c}$$

where, v = water velocity, m/s

$$Q = \text{flow rate, m}^3/\text{s}; \quad A_c = \text{cross-sectional area, m}^2$$

Example 5: The City of Richmond has a low-turbidity raw water and designing its overflow weir at a loading rate of 150 m³/d.m. If its plant flow rate is 0.5 m³/s, how many linear meters of weir are required?

Solutions:

$$\begin{aligned} \text{Weir Length} &= \frac{\text{Flow rate}}{\text{loading rate}} \\ &= \frac{0.5 \text{ m}^3/\text{s} \times 86,400 \text{ s/d}}{150 \text{ m}^3/\text{d.m}} = 288 \text{ m} \quad \text{ANS.} \end{aligned}$$

The configuration and depth of the **sludge storage zone** depends on the method of cleaning, the frequency of cleaning, and the quantity of sludge estimated to be produced.

With a well-flocculated solid and good inlet design, over 75% of the solids may settle in the 1st fifth of the tank.

For **coagulant floc**, Hudson recommends a sludge storage depth of about 0.3 m near the outlet and 2 m or more near the inlet.

- **Sedimentation Concepts:**

- Two important terms to understand in sedimentation zone design:
 - the velocity at which the tank is designed to operate, called *overflow rate*, v_o .
 - Particle (*floc*) *settling velocity*, v_s
- Overflow rate:

$$v_o = \frac{\text{Volume/Time}}{\text{Surface Area}} = \frac{(\text{Depth})(\text{Surface Area})}{(\text{Time})(\text{Surface Area})} = \frac{\text{Depth}}{\text{Time}} = \text{Liquid Velocity}$$

$$v_o = \frac{V/\theta}{A_s} = \frac{(h)(A_s)}{(\theta)(A_s)} = \frac{h}{\theta}$$

- * Here, θ is called *hydraulic retention or detention time*.

Example 6: A water treatment plant settling tank has a vertical overflow rate of 600 gal/day-ft² and a depth of 6 ft. What is its retention time?

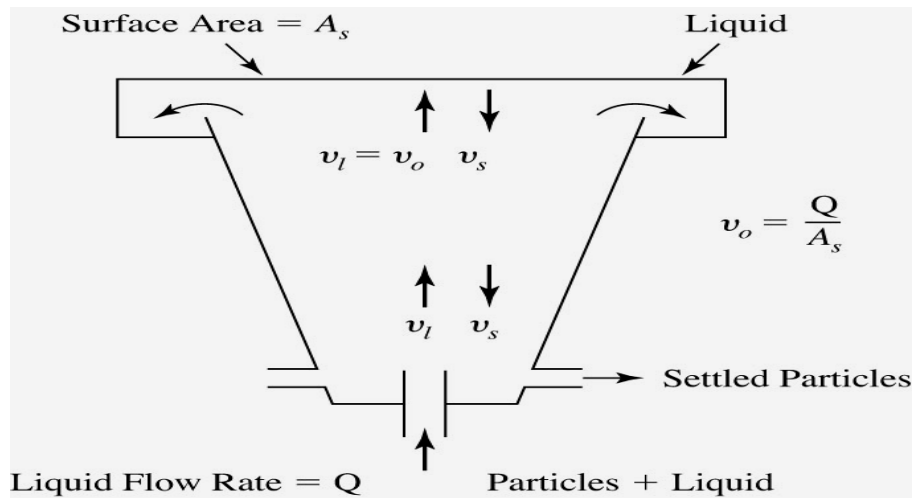
Solutions:

$$v_o = \frac{600 \text{ gal/day} \cdot \text{ft}^2}{7.48 \text{ gal/ft}^3} = 80.2 \text{ ft/day}$$

$$\therefore \text{retention time, } \theta = \frac{h}{v_o} = \frac{6 \text{ ft.}}{80.2 \text{ ft/day}}$$

$$= 0.0748 \text{ days} \cong 2 \text{ hours. ANS.}$$

- **For vertical overflow rate:**
- If $v_s > v_o$: one would expect 100% particle removal
- If $v_s < v_o$: one would expect 0% removal
- In design, the procedure would be to determine the v_s and set the value for v_o at some lower value.
- Often, $v_o = 50\text{-}70\%$ of v_s for an upflow clarifier.



Settling in an upflow clarifier

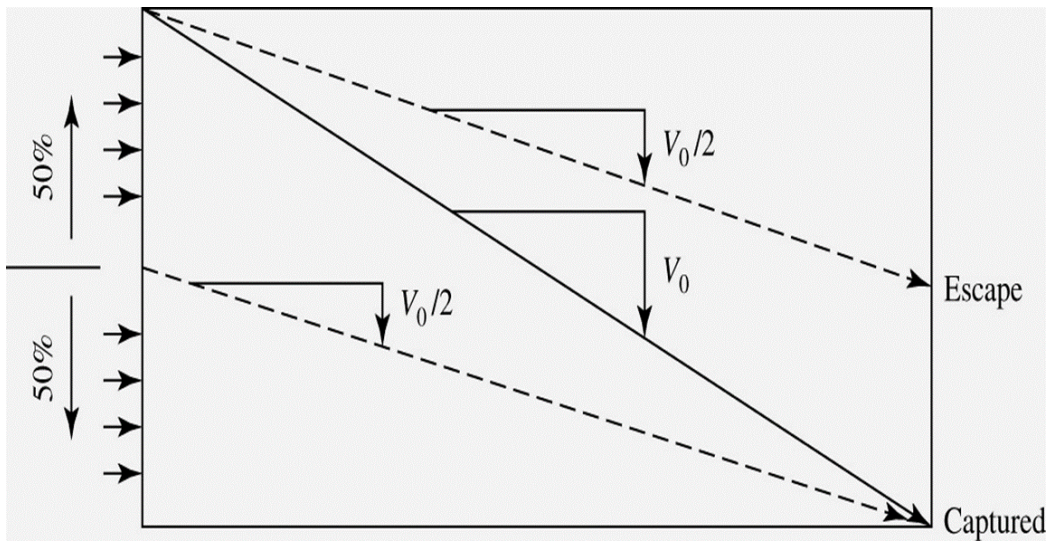
- **Sedimentation Concepts: Settling velocity (v_s) for horizontal flow**
- Settling velocity must equal the depth of the tank divided by the detention time, that is

$$v_s = \frac{h}{\theta} \quad \text{but} \quad \theta = \frac{V}{Q}$$

$$v_s = \frac{h}{V/Q} = \frac{hQ}{l \times w \times h} = \frac{Q}{l \times w} = \frac{Q}{A_s}$$

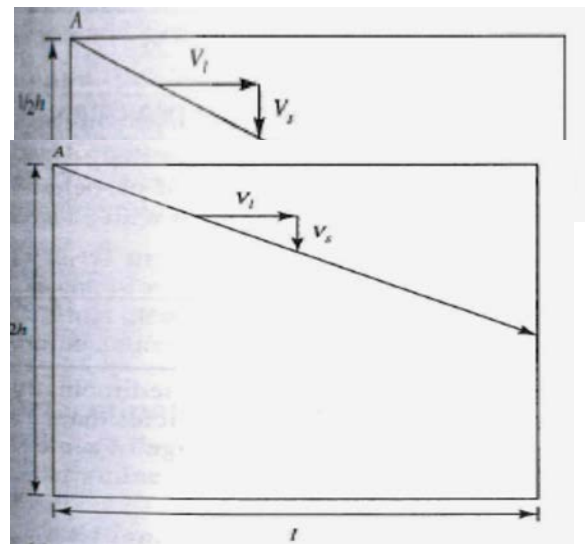
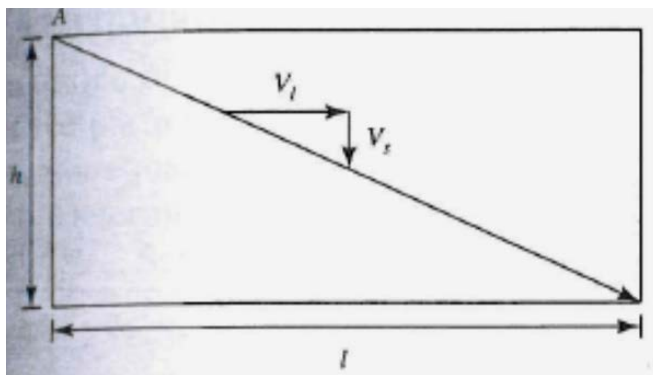
- Which is the overflow rate (v_o). This implies that the removal of a horizontal clarifier is independent of depth. This ambiguity can be clear with Figure 4-36b.

Sedimentation Concepts:

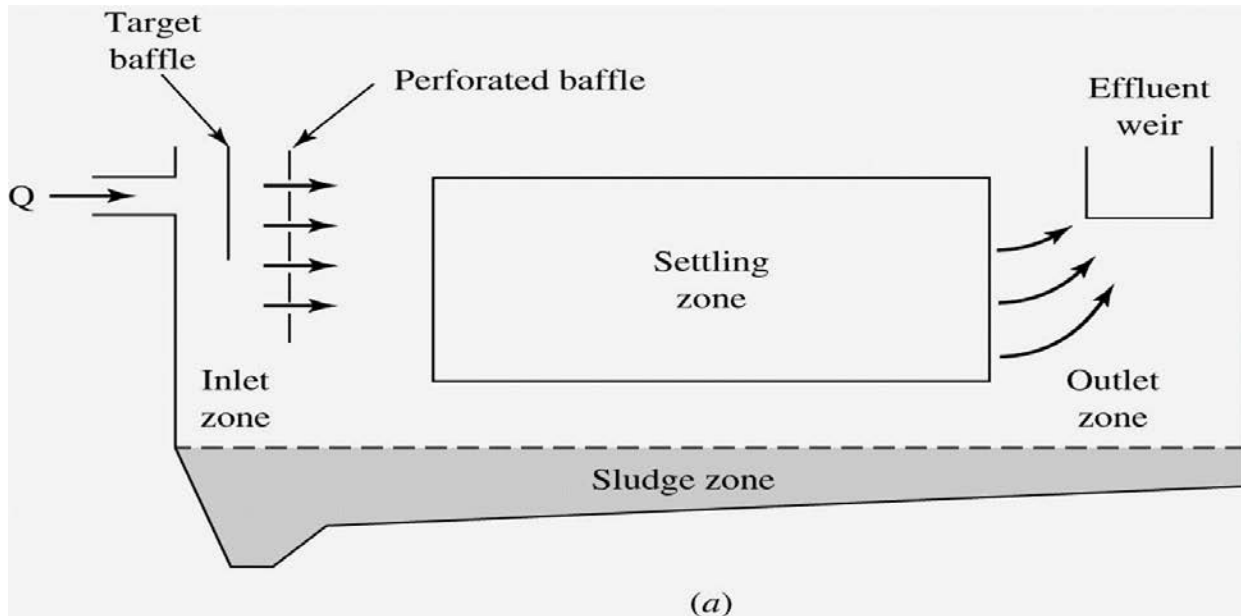


Partial solids removal in ideal sedimentation tank

- Settling velocity (v_s)



Ideal horizontal sedimentation tank



Zones of sedimentation on a horizontal flow clarifier

Sedimentation Concepts: Settling velocity (v_s) for horizontal flow

- Percentage of particles removed, P , with a settling velocity of v_s in a sedimentation tank design with an overflow rate of v_o is:

$$P = 100 \frac{v_s}{v_o}$$

- Let's say $v_o = 0.20$ mm/s, What % removal for particles with settling velocity = 0.15 mm/s?

$$P = 100 \frac{0.15}{0.20} = 75\%$$

Example 6: The city of Richmond has an existing horizontal flow sedimentation tank with an overflow rate of $17 \text{ m}^3/\text{d}\cdot\text{m}^2$, and it wishes to remove particles that have settling velocities 0.1 mm/s, 0.2 mm/s, and 1 mm/s. What % of removal should be expected for each particle in an ideal sedimentation tank.

Solutions:

Given overflow rate,

$$v_o = 17 \text{ m}^3/\text{d}\cdot\text{m}^2 = 17 \text{ m/d} \times 1\text{d}/86,400\text{s} \times 1000\text{mm}/1\text{m} = \underline{\underline{0.2 \text{ mm/s}}}$$

(a) $v_s = 0.1$ mm/s; since $v_s < v_o$ for a v_s of 0.1 mm/s, some fraction will be removed as

$$P = 100 \frac{v_s}{v_o} = 100 \frac{0.1}{0.2} = 50\%$$

(b) $v_s = 0.2$ mm/s; since $v_s = v_o$ for a v_s of 0.2 mm/s, 100% particle will be removed as

$$P = 100 \frac{v_s}{v_o} = 100 \frac{0.2}{0.2} = 100\%$$

(c) $v_s = 1$ mm/s; since $v_s > v_o$ for a v_s of 1 mm/s, 100% particle will be removed as

$$P = 100 \frac{v_s}{v_o} = 100 \frac{1}{0.2} \approx 100\%$$

- **Determination of v_s**
 - ✓ Determination of v_s is different for different types of particles. Settling properties of particles are often categorized into 3 classes:
- **Type I (Discrete) Sedimentation:**
 - ✓ This type is characterized by particles that settle discretely at a constant velocity. They settle as individual particles and do not flocculate or stick to other particles during settling. Examples are sand and grit material.
- **Type II (Flocculant) Sedimentation:**
 - ✓ This type is characterized by particles that flocculate during sedimentation. Since they flocculate, the size is constantly changing; therefore, the settling velocity is changing (i.e., increasing).
 - ✓ These types of particle settlings occur in alum or iron coagulation in primarily sedimentation, and in settling tanks in trickling filter.
- **Type III (Hindered or Zone) Sedimentation:**
 - ✓ In zone sedimentation the particles are at high concentration ($> 1,000$ mg/L) such that the particles tend to settle as a mass or blanket, and a distinct clear zone and sludge zone are present.

Zone settling occurs in lime softening sedimentation, activated sludge sedimentation, and sludge thickening.

- **Terminal Settling velocity (v_s):** - Five ways to determine v_s and consequently overflow rates (v_o) such as:

1. Calculations (Type I Sedimentation)
2. Flocculant Sedimentation Lab or Pilot Data (Type II Sedimentation)
3. Zone Sedimentation Lab Data (Type III Sedimentation)
4. Jar Test Data
5. Experience

- **Terminal Settling velocity (v_s): Calculations:**

- In the case of Type I sedimentation, the particle-settling velocity can be calculated, and basin designed to remove a specific size particle.
- Sir Isaac Newton showed that a particle falling in a quiescent fluid accelerate until the *frictional resistance*, or *drag*, on the particle is equal to the *gravitational force* of the particle.
- The three forces are defined as:

$$F_G = (\rho_s)gV_P$$

$$F_D = C_D A_P (\rho) \frac{v^2}{2}$$

$$F_B = (\rho)gV_P$$

where, F_G = gravitational force

F_B = buoyancy force

F_D = drag force

ρ_s = density of particle, kg/m^3

ρ = density of fluid, kg/m^3

g = acceleration due to gravity, m/s^2

V_P = volume of particle, m^3

C_D = drag coefficient

A_P = cross-sectional area of particle, m^2

v = velocity of particle, m/s

The driving force for acceleration of the particle is the difference between gravitation and buoyant force.

$$F_G - F_B = (\rho_s - \rho)gV_P$$

When the drag force is equal the driving force, the particle reaches a constant value called the *terminal settling velocity* (v_s).

$$F_G - F_B = F_D$$

$$(\rho_s - \rho)gV_P = C_D A_P (\rho) \frac{v_s^2}{2}$$

- For spherical particle with a diameter = d ,

$$\frac{V_P}{A_P} = \frac{\frac{4}{3}(\pi)(d/2)^3}{(\pi)(d/2)^2} = \frac{2}{3}d$$

- Solving the above equation for *terminal settling velocity* (v_s).

$$v_s = \left[\frac{4g(\rho_s - \rho)d}{3C_D\rho} \right]^{1/2}$$

- For viscous resistance at low Reynolds numbers ($R < 0.5$) for spheres:

$$C_D = \frac{24}{R}$$

- For transition region of R between 0.5 to 10^4 , C_D is approximated as

$$C_D = \frac{24}{R} + \frac{3}{R^{1/2}} + 0.34$$

- Sir George Gabriel Stokes showed that, for spherical particles falling under laminar (quiescent) conditions, the equation for *terminal settling velocity* (v_s) becomes as follows:

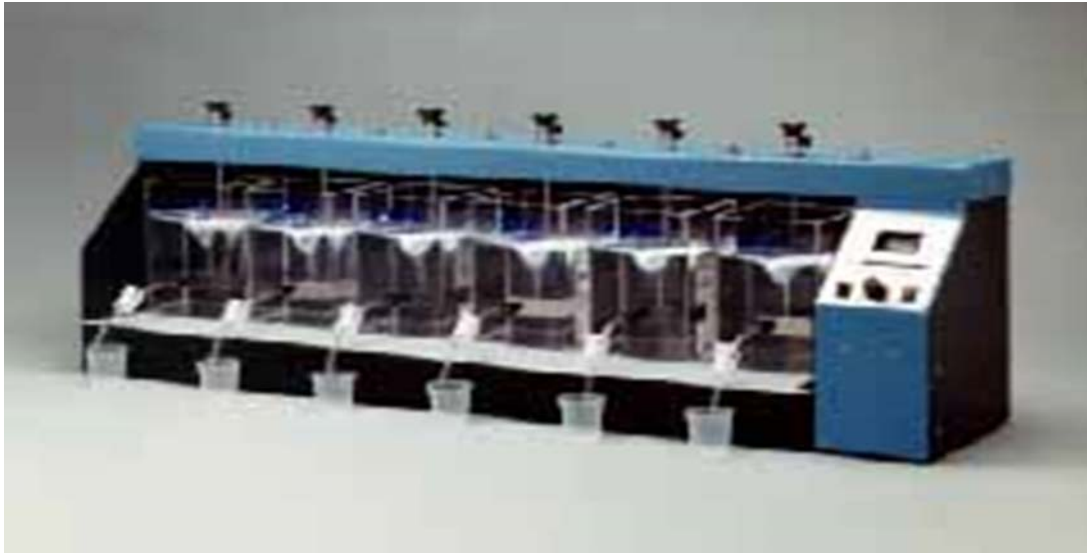
$$v_s = \frac{g(\rho_s - \rho)d^2}{18\mu}$$

where, μ = dynamic viscosity, Pa.s (also called absolute viscosity
and is a function of water temperature)

$d = \text{diameter of sphere, } m$

$18 = \text{a constant}$

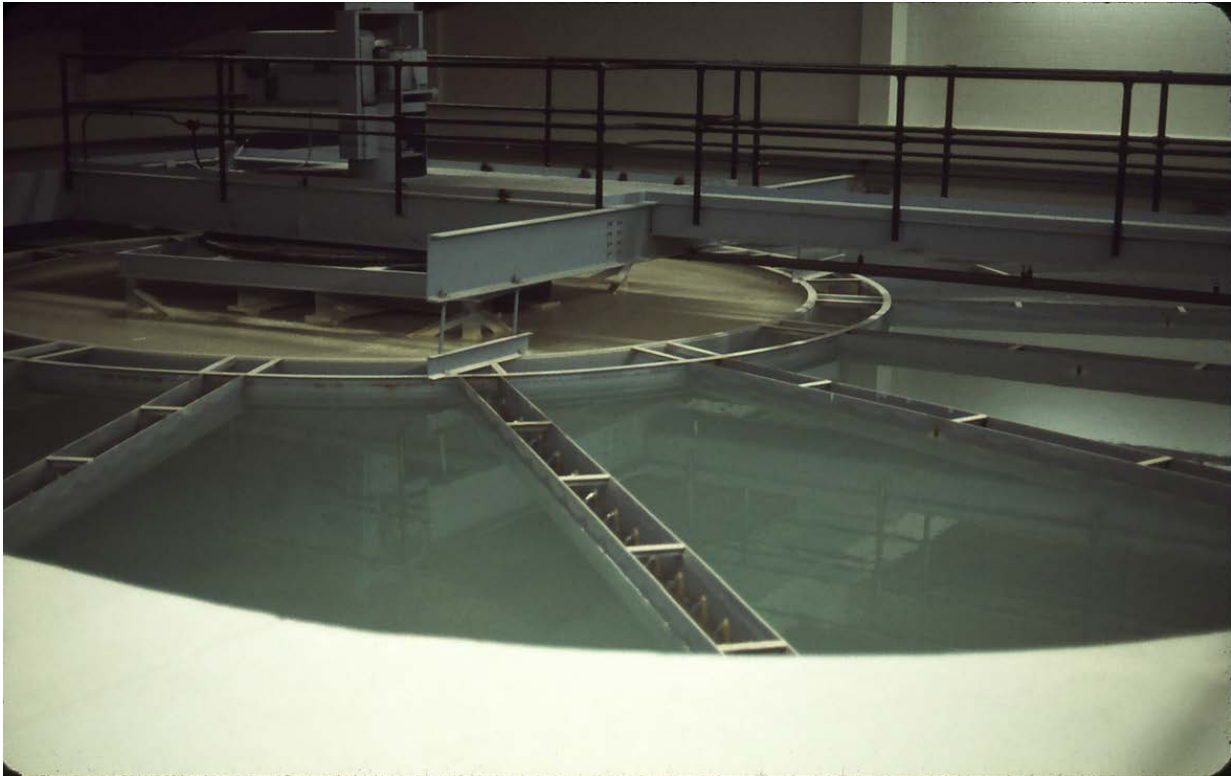
- The above equation is called *Stokes' Law*.
- Fair, Geyer, and Okun (1968) recommended, $v_o = 0.33$ to 0.7 times of v_s
- **Terminal Settling velocity (v_s): Flocculant Sedimentation Lab or Pilot Data (Type II Sedimentation):**
 - ✓ The stokes equation cannot be used because the flocculating particles are continually changing in size and shape, and when water is entrapped in the floc, in specific gravity.
 - ✓ Lab data with settling columns are used to develop design data.
- **Terminal Settling velocity (v_s): Flocculant Sedimentation Lab or Pilot Data (Type II Sedimentation):**
 - ✓ Settling column is filled with the suspension to be analyzed and the suspension is allowed to settle.
 - ✓ Samples are withdrawn from the sample ports at selected time intervals. Concentration of suspended solid is determined for each sample and the % removal is calculated:
- **Terminal Settling velocity (v_s): Zone Sedimentation Lab Data (Type III Sedimentation):**
 - For zone sedimentation, values can be obtained from the lab. The design overflow (v_o) is set at about 0.5 to 0.7 times of the lab value.
- **Terminal Settling velocity (v_s): Jar Test Data:**
 - A technique has been developed to determine settling velocities (v_s) of coagulant **flocs** from Jar test data, but it is not discussed in this course.



- **Terminal Settling velocity (v_s):** Experience
 - ✓ Typical design numbers exist for all types of sedimentation basins. These numbers can be used in lieu of laboratory or pilot work.
 - ✓ The typical numbers are quite conservative
 - ✓ Typical detention times for waters coagulated with alum or iron salts are on the order of 2 to 8 hours. In lime-soda softening plants, the detention times range from 4 to 8 hours.

Application	Long rectangular and circular ($m^3/d \cdot m^2$)	Upflow solids-contact, ($m^3/d \cdot m^2$)
<i>Alum or iron coagulation</i>		
Turbidity removal	40	50
Color removal	30	35
High algae	20	
<i>Lime softening</i>		
Low magnesium	70	130
High magnesium	57	105
Source: AWWA, 1990.		

- **Terminal Settling velocity (v_s):** Experience



Settling tank with radial weirs

Terminal Settling velocity (v_s): Experience



Rectangular settling tank with longitudinal weirs¹



Circular settling tank with radial weirs²

▪ **Sedimentation Tank Design:**

- ✓ Common length-to-width ratio = 2:1 to 5:1 and length should not exceed 100 m (328 ft.).
 - ✓ Maximum depth = 5 m (16 ft).
- Column tests are performed to find the optimum detention time and overflow rate.
- Literature also provides values for detention time and overflow rate that can be obtained from column experiments.

Condition	Range (m ³ /m ² ·d)	Typical (m ³ /m ² ·d)
Primary clarification prior to secondary treatment		
Average flow	30–50	40
Peak flow	70–130	100
Primary clarification with waste-activated sludge return^a		
Average flow	25–35	30
Peak flow	45–80	60

^aIn many designs the waste-activated sludge is returned to the primary sedimentation basin. The objective is to concentrate the secondary sludge in the primary sedimentation basin.
 Note: 1 m³/m²·d = 24.5424 gpd/ft².

Overflow Rate (m ³ /m ² ·d)	Detention Period (h)					
	2.0-m Depth	2.5-m Depth	3.0-m Depth	3.5-m Depth	4.0-m Depth	4.5-m Depth
30	1.6	2.0	2.4	2.8	3.2	3.6
40	1.2	1.5	1.8	2.1	2.4	2.7 ^a
50	1.0	1.2	1.4	1.7	1.9	2.2
60	0.8	1.0	1.2	1.4	1.6	1.8
70	0.7	0.9	1.0	1.2	1.4	1.5
80	0.6	0.8	0.9	1.1	1.2	1.4

^aA 4.5-m deep sedimentation basin having an overflow rate of 40 m³/m²·d (982 gpd/ft²) will provide a detention period of 2.7 h. This may be the most desirable design condition.

Example 7: Determine the surface area of a settling tank for the City of Richmond's 0.5 m³/s design flow using the design overflow rate of 32.5 m³/d·m². Compare this surface area with that which results from assuming a typical conservative overflow rate of 20 m³/d·m². Find the depth of the clarifier for the overflow rate of 32.5 m³/d·m² and detention time 95 min for a length to width ratio of 4.5:1, maximum length is 100 m and maximum depth is 5 m. Provide minimum 2 tanks.

Solutions:

Data given:

$$Q = 0.5 \text{ m}^3/\text{s} = 0.5 \text{ m}^3/\text{s} \times \frac{86,400 \text{ s}}{1 \text{ d}} = 43,200 \text{ m}^3/\text{d}$$

Overflow rate, $v = 32.5 \text{ m}^3/\text{d}\cdot\text{m}^2$, conservative, $v = 20 \text{ m}^3/\text{d}\cdot\text{m}^2$
detention time, $t = 95 \text{ min}$. $L_{\text{max}} = 100 \text{ m}$. $d_{\text{max}} = 5 \text{ m}$
 $L:W = 4.5:1$. Number of tank = 2

Settling tank surface area, $SA = \frac{Q}{v} = \frac{43,200 \text{ m}^3/\text{d}}{32.5 \text{ m}^3/\text{d}\cdot\text{m}^2} = 1329 \text{ m}^2$
SA for conservative v , $SA_{\text{cons.}} = \frac{43,200 \text{ m}^3/\text{d}}{20 \text{ m}^3/\text{d}\cdot\text{m}^2} = 2160 \text{ m}^2$

Surface area is $\frac{2160 - 1329}{1329} \times 100 = 62.5\%$ higher w/conservative v

The design surface area for the tank = 1329 m²

Vol^m of tank, $V = Q \times t = 0.5 \text{ m}^3/\text{s} \times 95 \text{ min} \times \frac{60 \text{ s}}{1 \text{ min}}$
 $= 2850 \text{ m}^3$

$$\text{tank depth (liquid), } d = \frac{V}{SA} = \frac{2850}{1329} = 2.14 \text{ m} < d_{\text{max}} \text{ OK.}$$

$$\text{Surface area for each tank} = \frac{1329}{2} = 664.5 \text{ m}^2$$

$$SA = L \times W = 4.5 W^2 = 664.5 \text{ m}^2$$

$$\therefore W = \sqrt{\frac{664.5}{4.5}} = 12.15 \text{ m}$$

$$L = 4.5 W = 54.68 \text{ m} < L_{\text{max}} \text{ OK}$$

Dimension of each tank:

$$V_{\text{provided}} = 2 \times 54.68 \times 12.15 \times 2.15 = 2857 \text{ m}^3 > V_{\text{req.}}$$

$$L = 54.68 \text{ m}$$

$$W = 12.15 \text{ m}$$

$$d = 2.15 \text{ m} + \text{freeboard} + \text{sludge depth.}$$

If the L_{max} requirement is not met, increase the number of tanks and recalculate the "L" and "W".

Example 8: You are asked to *design a water treatment plant settling tank (length, width, depth, and check for volume provided)* after coagulation for the City of Austell. The design flow is 0.85 m³/s and the overflow rate and the detention time found from the column test are 35 m/d and 94.5 min, respectively. The City of Austell is asking you to keep the tank length maximum of 50 m and length-to-width ratio maximum of 4 to 1.

Example 8: Solutions

Given,					
Design flow, $Q =$	0.85	m ³ /s x (86,400 s/1 day)		73,440	m ³ /d
Over flow rate, $v_o =$	35	m/d			
Detention time, $t =$	94.5	min.			
$L_{\text{max}} =$	50	m			
L: W ratio =	4	:1		$\therefore L = 4W$	
Surface area, $SA = Q/v_o =$	(73440 m ³ /d)/(35 m/d)				
	=	2,098.29	m ²		
Total volume required, $V_{\text{req}} = Q \times t =$	(0.85 m ³ /s) x (94.5 min.) x (60 s/1 min.)				
	=	4819.5	m ³		
Depth, $d = V/SA =$	4819.5 m ³ / 2098.29 m ²				
	=	2.30	m plus sludge depth and freeboard		

Example 8: Solutions – cont’d

Tank Dimensions according to given parameters inputted from above:							
Assuming Number of Tank =	1	Probable number of tanks necessary = SA / (Lmax x W) =	2098.29 / (50 x 50 / 4) =	8			
Surface area of each tank, A =	Volume / (d x 1) =	4819.5 / (2.3 x 1) =	2098.29	m ²			
Surface Area, A = L x W =	4W x W	W = (2098.29/4) ^(1/2) =	22.90	m			
		and L = 4W = 4 x 22.9 =	91.61	m			
Check for Lmax:	Lmax is NOT OK, Change the number of tank =			8			
	Surface area for each tank, A =	4819.5 / (2.3 x 8) =	262.29	m ²			
		W = (262.29/4) ^(1/2) =	8.10	m			
	and	L = 4.5 W =	32.39	m			
		Lmax is OK.					
Check: Total volume provided =		32.39 x 8.1 x x 8 =	4819.50	m ³			
			>= Volume required, OK.				
P.S.: In practice, even number of tanks are provided. In this case you can provide 8 tanks. If the number is odd, add one more tank.							

15. Filtration

- The water leaving the sedimentation tank still contains floc particles.
- The settled water turbidity ranges from 1 to 10 TU with a typical value of 3 TU.
- In order to reduce this turbidity to 0.3 TU, a filtration process is used.
- **Classification of Filters:**
 - Based on type of medium used such as sand, coal (called anthracite), **dual media** (coal plus sand), or **mixed media** (coal, sand, and garnet).
 - **Based on allowable loading rate:** Loading rate is the flow rate of water applied per unit area of the filter. It is the velocity of water approaching the face of the filter.

$$v_a = \frac{Q}{A_s}$$

where, v_a = face velocity, m/d = loading rate, $m^3/d.m^2$.

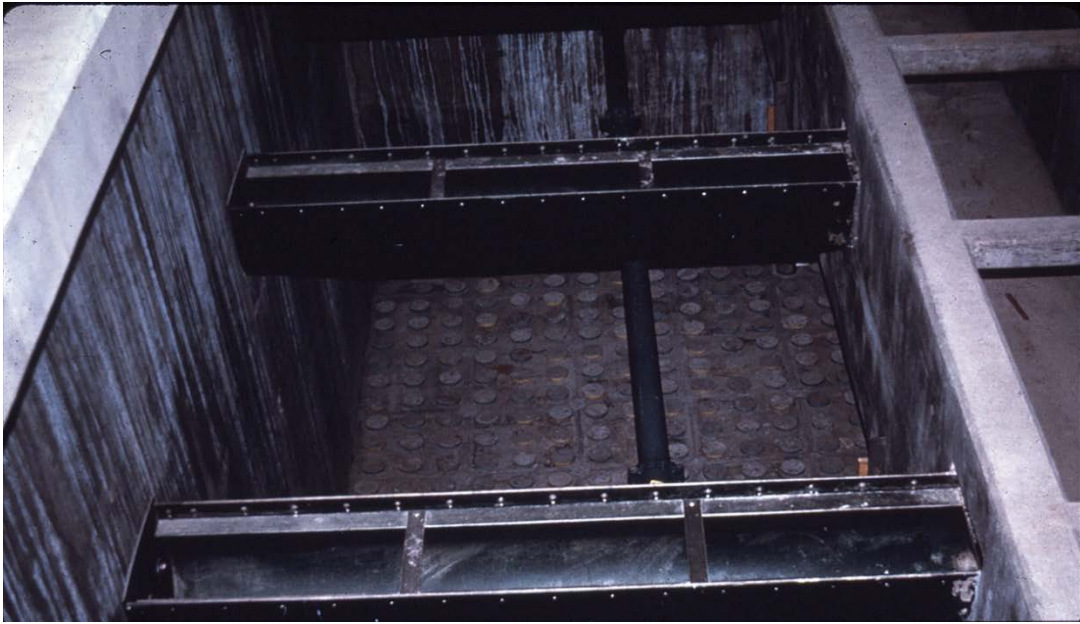
Q = flow rate on filter surface, m^3/d

A_s = surface area of filter, m^2 .

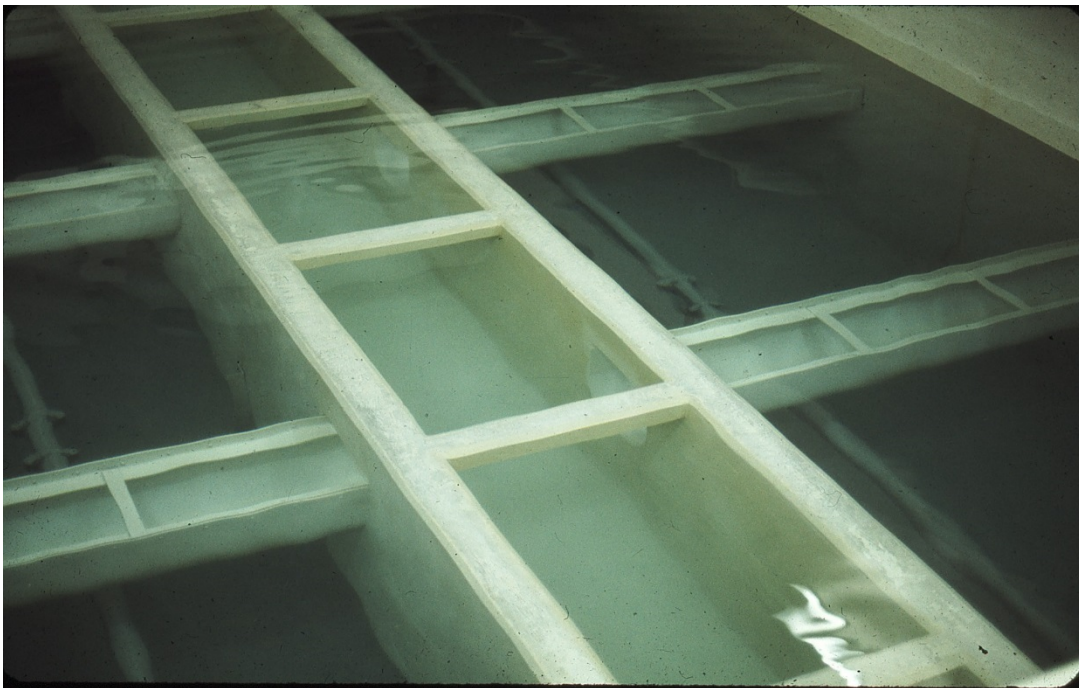
- Based on loading rate, the filters are classified as *slow sand filter*, *rapid sand filter*, or *high-rate sand filters*.

- **Slow Sand Filters:**
 - First introduced in the 1800s.
 - Loading rate = 2.9 to 7.6 $m^3/d.m^2$
 - As the suspended or colloidal material is applied to the sand, the particles begin to collect in the top 75 mm and to clog the pore spaces.
 - As the pore spaces clogged, water will no longer pass through the sand.
 - Top layer of sand is scrapped off, cleaned, and replaced.
 - It requires large areas of land and are operator intensive.

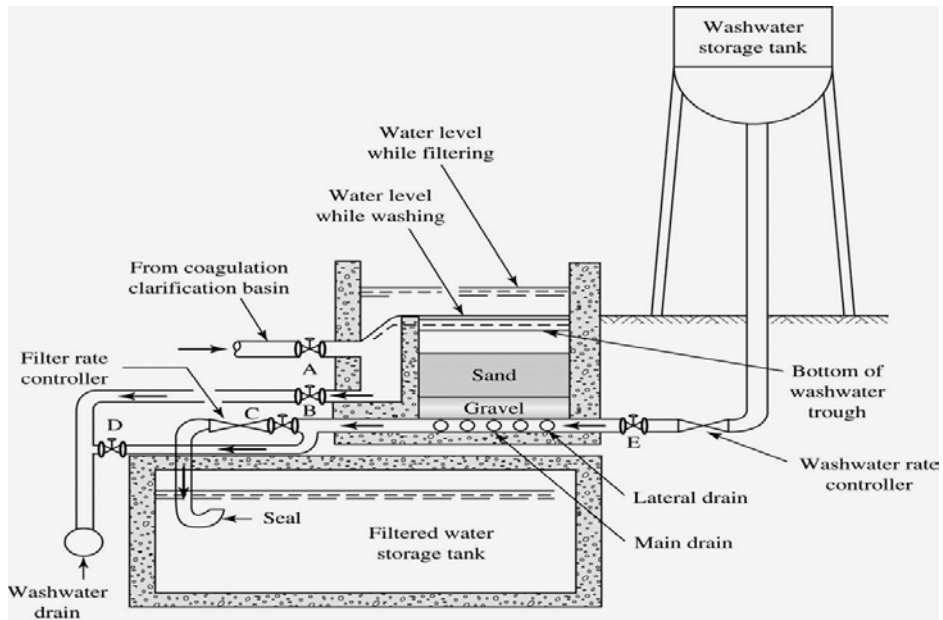
- **Rapid Sand Filters:**
 - First developed in the 1900s when large number of filtration systems need to be employed to prevent epidemics.
 - RSFs have *graded* (layered) sand in bed.
 - The sand grain size distribution is selected to optimize the passage of water while minimizing the passage of particulate matter.
 - RSFs are cleaned in place by forcing water backwards through the sand, called *backwashing*.
 - Loading rate up to 120 - 235 $m^3/d.m^2$
 - Normally, a minimum of 2 filters are constructed to ensure redundancy.
 - For larger plants ($> 0.5 m^3/s$), a minimum of 4 filters is suggested.
 - Maximum surface area = 100 m^2



Rapid sand filter with exposed under drain block. Wash water troughs run from left into gullet on right.



Rapid sand filter during filtration. Reflection shows water level above gullet and backwash troughs.



Operation of rapid sand filter with backwash



Softening sludge lagoon. Winter view shows ice (light blue) where supernatant water is standing.



Overview of water treatment plant showing sludge lagoons and building housing treatment facilities.

- **Dual-Media Filters:**

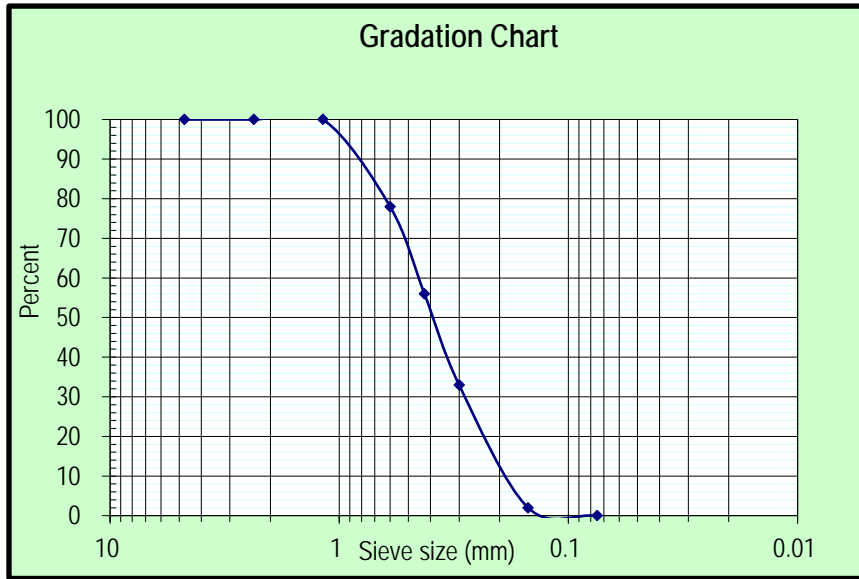
- Developed in in the wartime era of the early 1940s.
- Utilize more of the filter depth to remove particle.
- Removal of larger particles on the top of the smaller particles that is accomplished by placing a layer of coarse coal on top of a layer of fine sand.
- Coal has lower specific gravity than sand, so after backwash, coal settles slower than sand and ends up on top.
- Loading rate up to = $300 \text{ m}^3/\text{d.m}^2$

- **Deep-Bed Monomedi Filters:**

- Came into use in mid 1980s. Designed to achieve higher loading rate and produce lower finished water turbidities.
- The filters consist of 1.0 - 1.5 mm diameter anthracite about 1.5 - 2.5 m deep.
- Loading rate up to = $800 \text{ m}^3/\text{d.m}^2$

- **Grain size distribution:**

- For silica sand effective size (D_{10}) = 0.35 to 0.55 mm with a max. of 1.0 mm.
- Uniformity coefficient ($U = D_{60}/D_{10}$) = 1.3 to 1.7



$$D_{10} = 0.19 \text{ mm}$$

$$D_{60} = 0.45 \text{ mm}$$

$$U = 0.45/0.19 = \underline{2.368}$$

- **Filter Hydraulics:**

- The loss of pressure (head loss) through a filter media with uniform porosity is expressed by (Rose, 1954):

$$h_L = \frac{1.067v_a^2 D}{\phi g n^4} \sum_{i=1}^n \frac{C_D f}{d}$$

Where, h_L = frictional head loss through the filter, m

v_a = approach velocity, m/s

D = depth of filter sand, m

C_D = drag coefficient

f = mass friction of sand particles of diameter, d

d = diameter of sand particles, m

ϕ = shape factor; g = acceleration due to gravity, m/s²

n = porosity

- **Filter Hydraulics:**

- Initial head losses in excess of **0.6 m** indicate that either the loading rate is too high, or the sand has too large of fine grain sizes.

16. Disinfection

Disinfection is used in water treatment to **reduce pathogens (disease causing microorganisms) to an acceptable level.**

Three categories of human enteric pathogens are normally of consequence: bacteria, viruses, and amebic cysts.

Water disinfectants must have the following properties:

Water disinfectants must have the following properties:

- They must destroy the kinds and numbers of pathogens that may be introduced into the water within a practicable period of time over an expected range of temperature.
- They must meet possible fluctuations in composition, concentration, and condition of the waters or wastewaters to be treated.
- They must be neither toxic to humans and domestic animals nor unpalatable or otherwise objectionable in required concentrations.
- They must be dispensable at reasonable cost and safe and easy to store, transport, handle, and apply.
- Their concentration or strength in the treated water must be determined easily, quickly, and (preferably) automatically.
- They must persist within disinfected water in a sufficient concentration to provide reasonable residual protection against its possible recontamination before use.

Disinfection kinetics:

- **Chick's Law:** Number of organisms destroyed in a unit time is proportional to the number organisms remaining:

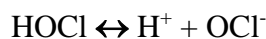
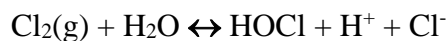
$$-\frac{dN}{dt} = kN$$

- This is a first-order reaction. The solution is:

$$N = N_0 e^{-kt}$$

- **Disinfection Mechanisms: By Chlorine**

- ✓ The term chlorination is often used synonymously with disinfection.
- ✓ Chlorine may be used as the element (Cl_2), as sodium hypochlorite (NaOCl), or as calcium hypochlorite [$\text{Ca}(\text{OCl})_2$].
- ✓ When chlorine is added with water, a mixture of hypochlorous acid (HOCl) and hydrochloric acid (HCl) is formed.



- ✓ Chlorine (specially the elemental chlorine, Cl_2) reacts with protein and amino acids of cells to alter and ultimately destroy cell protoplasm.
- ✓ Chlorine also react with humic substances present in water to form **trihalomethanes** (THMs, e.g., chloroform, bromoform, etc.) which are suspected human carcinogens (**Note: According to USEPA, maximum allowable level of THMs in drinking water is 80 $\mu\text{g/L}$**).
- ✓ Microorganisms killed by disinfectants is assumed to follow the *CT* concept, that is, the product of disinfectant concentration (C) and time (T) yields a constant.

$$CT = 0.9847C^{0.1758} \text{pH}^{2.7519} \text{temp}^{-0.1467}$$

C = disinfectant conc.; pH = $-\log[\text{H}^+]$; temp = temperature in $^{\circ}\text{C}$; T = contact time

- At least 99.9% (3-logs) reduction (removal and/or inactivation) of *Giardia lamblia*.
- At least 99.99% (4-logs) reduction (removal and/or inactivation) of viruses.
- **REMOVAL** = physically removing the organism from the water (by filtration or settling)
- **INACTIVATION (disinfection)** = modifying the organism so that it is no longer is pathogenic (by chemical treatment to destroy the cell's walls, or UV disinfection which affects genetic material (RNA or DNA) so the organism cannot reproduce)
- **Disinfection Mechanisms: By Chlorine – cont'd:**
 - “x” log removal means $x = -\log(1 - \% \text{ removal}/100)$ e.g. $0.5 = -\log(1 - 68/100)$

“x” LOG	% Removal
0.5	68
1	90
2	99
3	99.9
4	99.99

- The equation means that the combination of concentrations and time (CT) required to produce a 3-log reduction in Giardia cysts by chlorine can be estimated.
- Log removal can be found as:

$$LR = \log\left(\frac{\text{influent concentrations}}{\text{effluent concentrations}}\right)$$

$$\% \text{ Removal} = 100 - \frac{100}{10^{LR}}$$

- **Disinfection Mechanisms: CT Values in mg-min/L**

Table 2: CT Values for Inactivation of Viruses by Free Chlorine, pH 6-9

Inactivation (Log)	Water Temperature (°C)															
	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	1.0	1.0	1.0	1.0	1.0
3	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0
4	6.0	5.6	5.2	4.8	4.4	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0

- **Contact time,** $T(\text{min}) = \frac{\forall_{\text{eff}} (\text{gal}) \times BF}{Q_{\text{peak}} (\text{gal} / \text{min})}$
- **BF = Baffle Factor = 0.1 to 1.0**
- We can determine the inactivation with chlorine using
- “CT” calculations. (CT = C x T)
 - ✓ C = mg/L free chlorine in the water where the inactivation is occurring (tanks, pipelines, etc)

- ✓ T = minutes of contact time with the disinfectant in each segment, prior to first consumer.
- Contact time *T* depends upon the effective volume V_{eff} (e.g. volume of the tank holding liquid at a given time), the hydraulics of flow (use of a Baffling Factor BF), and the peak flow (gpm) through the segment.
- Baffling factors (BF or T10/T) are adjustment factors or fractions usually less than 1 -- multipliers to get the actual detention or contact time.
- BF are used because there may be “dead zones” where water bypasses part of the volume of the tank or chamber.
- **Formulas for effective volume calculations:**
 - ✓ Cylindrical Tank: $V = 0.785 \times \text{diameter}^2 \times \text{height}$
 - ✓ Pipeline: $V = 0.785 \times \text{diameter}^2 \times \text{length}$
 - ✓ Rectangular Clearwell: $V = \text{length} \times \text{width} \times \text{depth}$
- **Baffle**

Baffling Condition	T10/T*	Baffling Description
Unbaffled	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities, unbaffled, inlet and outlet at the same levels.
Unbaffled	0.2	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities, unbaffled, inlet/high and outlet/low or visa versa.
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles, vertical perforated pipe for an inlet and/or outlet.
Average	0.5	Baffled inlet or outlet, vertical perforated pipe for an inlet or outlet, with some intra-basin baffles.
Superior	0.7	Perforated inlet baffle, perforated intra-basin baffles, outlet weirs or perforated launders.
Excellent	0.9	Serpentine Baffling throughout
Perfect	1.0	Pipeline flow

*T10 = detention time at which 90% of the water passing through the unit is retained

- **Disinfection By Ozone:**
 - ✓ **Ozone** has long been used as a disinfectant in water and wastewater application.

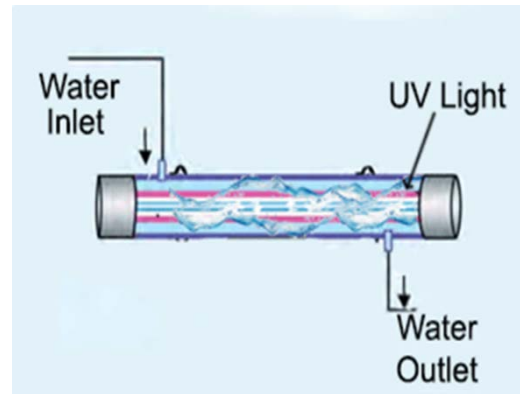
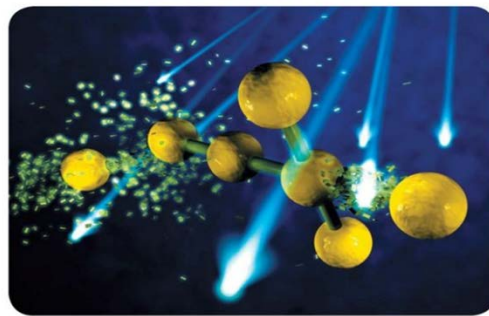
- ✓ Ozone is a blue gas at normal temperatures and pressures and has a recognizable pungent odor. It is irritating to mucous membranes and is a significant surface air pollutant in many areas.

▪ **Disinfection By Ultraviolet Radiation:**

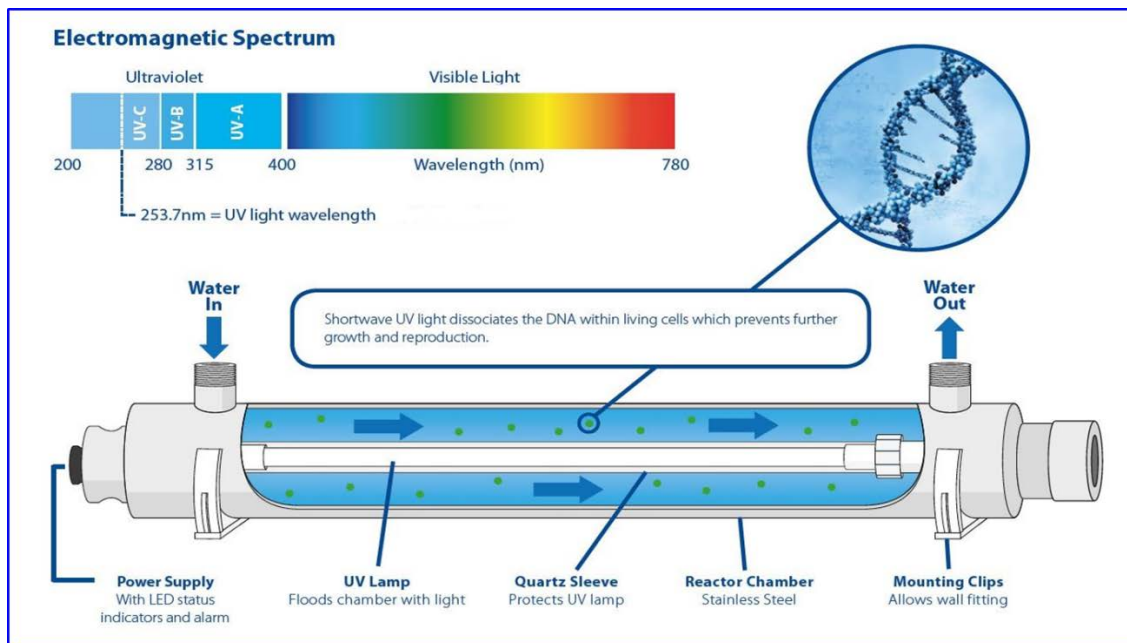
- ✓ Ultraviolet radiation is used to kill the pathogens.



**ULTRAVIOLET (UV) RADIATION
DISINFECTION**



▪ **Disinfection By Ultraviolet Radiation²:**



17. Adsorption

Adsorption is a mass transfer process wherein a substance is transferred from the liquid phase to the surface of a solid where it binds by chemical or physical forces.

In water treatment, the adsorbent (solid) is activated carbon either granular activated carbon (GAC) or powdered activated carbon (PAC).

PAC is fed to the raw water in a slurry and used to **remove taste- and odor causing substances** or to provide some removal of synthetic organic chemicals (SOC).

GAC is added to the filter system by replacing the anthracite with GAC or an additional contractor is built with GAC.

GAC has been proposed to be used to remove naturally occurring organic matter that would, in turn, reduce formation of disinfection by-products (DBPs).

GAC usually lasts for 90-120 days until it loses its adsorption capacity.

18. Water Plant Waste Management

Sludge is the major waste of water treatment plant. The precipitate chemicals and other materials removed from raw water to make it palatable and potable are the main source of sludge production.

Sludge is most commonly produced from the processes of presedimentation, sedimentation, and filtration (filter backwash).

Major water treatment plant wastes (sludge) are:

Solid/Liquid Sludge

- Alum sludges
- Iron sludges
- Polymeric sludges
- Softening sludges
- Backwash sludges
- Spent GAC or discharge from carbon system
- slow sand filter wastes
- Wastes from iron and manganese removal plants
- Spent precoat filter media

- **Liquid-Phase Sludge**
 - Ion-exchange regenerant brine
 - waste regenerant from activated alumina
 - Reverse osmosis waste stream
- **Gas-Phase Sludge**
 - Air stripping off gas
- **Sludge management program attempts to use the following approach in disposing of the sludge:**
 - 1. Minimization of sludge generation
 - 2. Chemical recovery of precipitates
 - 3. Sludge treatment to reduce volume
 - 4. Ultimate disposal in an environmentally safe manner
- **Sludge Production and Characteristics:**
 - Sludge is most commonly produced from the processes of presedimentation, sedimentation, and filtration (filter backwash).
- **Presedimentation:**
 - When surface waters are withdrawn from watercourses that contain a large quantity of suspended solids, presedimentation prior to coagulation may be practiced.
 - The purpose of presedimentation is to reduce the accumulation of solids in subsequent units.
 - Sludge in presedimentation process consists of fine sand, silt, clays, organic decomposition products.
- **Sludge Production and Characteristics:**
- **Softening sedimentation basin:**
 - Theoretically, each mg/L of calcium hardness removed produces 1 mg/L of CaCO_3 sludge.
 - Each mg/L of magnesium hardness removed produces 0.6 mg/L of Mg(OH)_2 sludge. The sludge production can be calculated as:

$$M_s = 86.40 Q (Ca_R + 0.58Mg_R + L_A)$$

where, M_s = dry sludge produced, kg/d

Q = plant flow rate, m^3/s

Ca_R = calcium hardness removed, mg/L as $CaCO_3$

Mg_R = magnesium hardness removed, mg/L as $CaCO_3$

L_A = lime added, mg/L as $CaCO_3$

- **Coagulation sedimentation basin:**

- Aluminum or iron salts are generally used to accomplish coagulation.
- Each kg of alum $[Al(H_2O)_3(OH)_3]$ -aluminum hydroxide complex] added produces 0.44 kg of chemical sludge
- Each kg of carbon, polymers, and clay produce about 1 kg of sludge. The sludge production for alum coagulation can be calculated as:

$$M_s = 86.40 Q (0.44A + SS + M)$$

where, M_s = dry sludge produced, kg/d

Q = plant flow rate, m^3/s

A = alum dose, mg/L

SS = suspended solids in raw water, mg/L

M = miscellaneous chemicals additions such as carbon, polymer, and clay, mg/L

- **Filter backwash:**

- All water treatment plants that practice filtration produce a large volume of wastewater containing a low suspended solids concentration.
- Wastewater volume = 2 - 3% of the treatment plant flow
- The solids in backwash water resemble those found in sedimentation units.
- Since filter can support biological growth, the filter backwash may contain a larger fraction of organic solids compared to solids from sedimentation basins.

- **Mass balance analysis:**

- Since there is no reaction taking place, the mass balance equation reduces to the form:

Accumulation Rate = Input Rate - Output rate

- The input rate may be calculated using equations for softening and coagulation sedimentation basins. To estimate the mass flow (output rate) of solids leaving the clarifier through the weir, the concentration of solids and the flow rate must be estimated.
- The mass flow out through the weir is then:

Weir output rate = (Concentration, mg/L)(Flow rate, m³/s) = mg/s.

- **Minimization of Sludge Generation**

- ✓ Minimization of sludge generation can have an advantageous effect on the requirements and economics of handling, treating, and disposing of sludges.
- ✓ Minimization also results in the conservation of raw materials, energy, and labor.

- **There are 3 methods of minimization:**

- ✓ Changing the water treatment process to direct filtration
- ✓ substituting other coagulants and in particular using polymers that are effective at lower doses.
- ✓ Conserving chemicals by determining optimum dosage at frequent intervals as raw water characteristics change.

- **Sludge Treatment**

- ✓ The required degree of treatment is a direct function of the ultimate disposal method.
- ✓ Sludge thickening, conditioning, and dewatering are the general categories of treatment.

- **Thickening:**

- ✓ Gravity thickening, equalization

- **Dewatering:**

- ✓ Dewatering Lagoon; Sand bed; Centrifuge; Pressure filter; Vacuum filter; and Belt filter press.

- **Ultimate Disposal of Sludge**

- After all possible sludge treatment has been accomplished, a residual sludge remains, which must be sent to ultimate disposal.

- Of many theoretical alternatives for ultimate disposal, only 3 are of practical interest:
 1. Co-disposal with sewage sludge
 2. Landfilling
 3. Land spreading (i.e., land application)
- Of these 3 methods, only last 2 are true ultimate disposal.

19. Summary

In this course we understood the principles of water treatment and unit processes, such as coagulation/flocculation, sedimentation, softening, filtration, adsorption, disinfection, etc. we defined several terms related to water supply systems, water supply systems classifications, and chemical units. We explained water chemistry, physical, chemical, biological, radiological characteristics of water, reaction kinetics, reactors, and water plant waste management. We solved several problems to understand the extent of water treatment and design some unit processes.

20. References

1. Introduction to Environmental Engineering by Mackenzie L. Davis and David A. Cornwell, McGraw-Hill Book Company.
2. Personal work experience and open source from internet.

+++++ **The End** +++++

Any questions please contact the instructor at makarim@juno.com

QUIZ for Basic Principles of Water Treatment

1. A public water system that regularly supplies water to at least _____ of the same people at least _____ month per year, but not year-round is called Non-Transient Non-Community Water System (NTNCWS); for instance, schools, hospitals, office, factories that have their own water system.
 - a. 25 people; 6 months
 - b. 25 people; 3 months
 - c. 50 people; 6 months
 - d. 25 people; 9 months

2. Conversion process of quick lime (CaO) to hydrated lime ($Ca(OH)_2$) is called _____.
 - a. slaking
 - b. hydration
 - c. carbonation
 - d. dehydration

3. EPA classifies water systems that supply water to 501 – 3,300 people as:
 - a. very Small water systems
 - b. Small water systems
 - c. medium water systems.
 - d. large water systems.

4. In order to perform stoichiometric calculations, it is necessary to convert to common units, and the terms _____ and _____ are used.
 - a. mg/mL and g/L
 - b. molarity (M) and Normality (N)
 - c. ppm and ppb
 - d. none of the above
 - e. all of the above

5. Define pathogen, potable, and palatable.
 - a. Pathogen = An organism which causes disease; Potable = Safe to drink; Palatable = Pleasing to drink
 - b. Pathogen = Safe to drink Potable = An organism which causes disease; Palatable = Pleasing to drink.
 - c. Pathogen = An organism which causes disease; Potable = Pleasing to drink; Palatable = Safe to drink.
 - d. Pathogen = Pleasing to drink; Potable = Safe to drink; Palatable = An organism which causes disease.

6. Physical Characteristics of water are:
- pH, color, and turbidity
 - turbidity, color, taste and odor, and temperature.
 - iron, chloride, inorganics, and organics
 - all of the above
 - none of the above
7. President Ford signed the National Safe Drinking Water Act (SDWA) into law on December 16, 1974.
- True
 - False
8. Groundwater are contaminated with bacteria, viruses or inorganic substances which could present a health hazard.
- True
 - False
9. Surface water may contain in high concentrations of calcium, iron, manganese, and magnesium - further classified as to its source - deep or shallow wells.
- True
 - False
10. Water treatment systems can be classified as simple as _____ , _____ , and _____.
- disinfection, filtration plants, and softening plants
 - disinfection, filtration, and adsorption plants
 - disinfection, filtration, and absorption plants
 - filtration, softening, and adsorption plants
11. Generally _____ plant is used to treat surface water and a _____ plant to treat groundwater.
- filtration; softening
 - filtration; adsorption
 - absorption; disinfection
 - softening; disinfection
12. Coagulation applies to the removal of large (diameter > 1 μm) particles.
- True
 - False
13. The objective of coagulation (and subsequently flocculation) is to turn the small particles of color, turbidity and bacteria into larger flocs, either as precipitates or suspended particles.
- True
 - False

14. Three key properties of coagulant are: _____, _____, and _____.

- a. Divalent cation; Nontoxic; Insoluble in neutral pH range
- b. Trivalent cation; Nontoxic; Insoluble in neutral pH range
- c. Trivalent cation; Toxic; Insoluble in neutral pH range
- c. Trivalent cation; Nontoxic; Soluble in neutral pH range

15. Hardness is defined as the sum of all monovalent cations.

- a. True
- b. False

16. The chemical processes used to soften water are a direct application of the law of _____.

- a. mass action
- b. energy action
- c. all of the above
- d. none of the above

17. When carbonate ions (CO_3^{2-}) must be supplied, the most common chemical chosen is sodium carbonate (Na_2CO_3). Sodium carbonate is commonly referred as _____ or _____.

- a. hydrated lime or lime
- b. soda ash or soda
- c. sodium chloride or sodium
- d. none of the above

18. The hardness in the water exchanges with an ion from the ion-exchange material. Generally, the ion exchanged with hardness is _____.

- a. sodium
- b. potassium
- c. calcium
- d. cadmium

19. When the ion-exchange material becomes saturated, no hardness will be removed. At this point _____ is said to have occurred.

- a. cutthrough
- b. bringthrough
- c. breakthrough
- d. exhaustion

20. The ion-exchange material can either be naturally occurring clays, called *zeolites*, or synthetically made resins.

- a. True
- b. False

21. During coagulation and softening the chemical reactions that take place in rapid mixing form precipitates. Either aluminum hydroxide or iron hydroxide form during coagulation, while _____ and _____ form during softening.
- calcium carbonate and magnesium hydroxide
 - calcium hydroxide and magnesium carbonate
 - calcium chloride and magnesium nitrate
 - calcium nitrate and magnesium chloride
22. The precipitate formed in the coagulation processes must be brought in contact with one another so _____ that they agglomerate and form larger particles, called *flocs*. This contacting process is called _____ and is accomplished by slow and gentle mixing.
- flocculation
 - coagulation
 - agglomeration
 - all of the above
 - none of the above
23. Regardless of the type of basin, the basin design can be divided into four zones and these are:
- Inlet, Outlet, and Sludge storage
 - Inlet, Settling, and Sludge storage
 - Inlet, Ingress, Outlet, and Sludge storage
 - Inlet, Settling, Outlet, and Sludge storage
24. The _____ is to facilitate the settling process. In an accurate design, the inlet and settling zones are each designed separately, and their lengths added together.
- settling zone
 - outlet zone
 - inlet zone
 - sludge storage
25. The _____ is designed so as to remove the settled water from the basin without carrying away any of the floc particles.
- settling zone
 - outlet zone
 - inlet zone
 - sludge storage
26. The Type I settling is characterized by particles that settle discretely at a constant velocity. They settle as individual particles and do not flocculate or stick to other particles during settling, for instance sand and grit material.
- True
 - False

27. The Type II settling follows the Stokes law because the flocculating particles are continually changing in size and shape, and when water is entrapped in the floc.

- a. True
- b. False

28. Based on loading rate, the filters are classified into two categories and these are:

- a. slow sand filter and rapid sand or high-rate sand filter
- b. slow sand filter and multimedia filter
- c. dual media filter and rapid sand or high-rate sand filter
- d. slow sand filter and deep bed monomedia filter

29. Rapid sand filters (RFS) are cleaned in place by forcing water backwards through the sand, called _____.

- a. backwashing
- b. forwardwashing
- c. cleanwashing
- d. all of the above
- e. none of the above

30. Loading rate for slow sand filter is _____ to _____ $m^3/d.m^2$.

- a. 1.0 to 2.5
- b. 2.9 to 7.6
- c. 120 to 235
- d. 200 to 300

31. Loading rate for rapid sand filter is _____ to _____ $m^3/d.m^2$.

- a. 1.0 to 2.5
- b. 2.9 to 7.6
- c. 120 to 235
- d. 200 to 300

32. Loading rate for dual media filter is up to _____ $m^3/d.m^2$.

- a. 2.5
- b. 7.6
- c. 235
- d. 300
- e. 800

33. Loading rate for deep-bed monomedia filter is up to _____ $m^3/d.m^2$.

- a. 2.5
- b. 7.6
- c. 235
- d. 300
- e. 800

34. _____ is used in water treatment to reduce pathogens (disease causing microorganisms) to an acceptable level.
- Adsorption
 - Disinfection
 - Absorption
 - All of the above
 - None of the above
35. Disinfection in water treatment can be accomplished by using _____, _____, _____.
- chlorine, ozone, and ultraviolet rays
 - bromine, ozone, ultraviolet rays
 - iodine, ozone, ultraviolet rays
 - fluorine, ozone, ultraviolet rays
36. _____ is a mass transfer process wherein a substance is transferred from the liquid phase to the surface of a solid where it bounds by chemical or physical forces.
- Adsorption
 - Absorption
 - Precipitation
 - Coagulation
37. Granular activated carbon (GAC) has been proposed to be used to remove naturally occurring organic matter that would, in turn, reduce formation of disinfection by-products (DBPs).
- True
 - False
38. Powdered activated carbon (PAC) is fed to the raw water in a slurry and used to remove taste- and odor causing substances or to provide some removal of synthetic organic chemicals (SOC).
- True
 - False