Chapter 3

Drinking Water Quality & Treatment

SOURCES:

- Groundwater : Springs , Artesian wells
- Surface water : Rivers, Lakes, The sea (Desalination plants)

Groundwater

- constant composition
- high mineral content
- low turbidity
- low color
- low or no D.O.
- high hardness
- high Fe, Mn

Surface water

- variable composition
- low mineral content
- high turbidity
- colored
- D.O. present
- low hardness
- taste and odor

Dr. Ahmad AbuYaghi Feb. 2022

Objectives of Water Treatment

- <u>The goal of municipal water treatment is **to provide water:**</u>

1. With quality that meets regulatory criteria or standards to be both
   - ❑ **<u>potable</u>**
     - Safe to drink – protective of human health
     - Not necessarily esthetically pleasing, <u>and</u>
   - ❑ **<u>palatable</u>**
     - esthetically pleasing
     - presence of chemicals does not pose a threat to human health
     - includes chloride, color, corrosivity, iron, manganese, taste and odor
2. In sufficient quantity that is continuous without interruption, and
3. At reasonable cost.

Water Quality

- Defined in relation to intended use
  - Drinking water,
  - irrigation,
  - power generation, etc.
- Water Quality Parameters:
  - A. Physical (Aesthetic or Acceptability),
  - B. Chemical,
  - C. Radioactive,
  - D. Microbiological.

Table 22.2 National Drinking Water Standards

Contaminant	*Maximum Contaminant Level (mg/l)*
Inorganics	
Arsenic	0.05
Cadmium	0.01
Lead	0.015 action level[a]
Mercury	0.002
Selenium	0.01
Organic chemicals	
Pesticides	
Endrin	0.0002
Lindane	0.004
Methoxychlor	0.1
Herbicides	
2,4-D	0.1
2,4,S-TP	0.01
Silvex	0.01
Volatile organic chemicals	
Benzene	0.005
Carbon tetrachloride	0.005
Trichloroethylene	0.005
Vinyl chloride	0.002
Microbiological organisms	
Fecal coliform bacteria	1 cell/100 ml

[a] Action level is related to the treatment of water to reduce lead to a safe level. There is no maximum contaminant level for lead.
Source: U.S. Environmental Protection Agency.

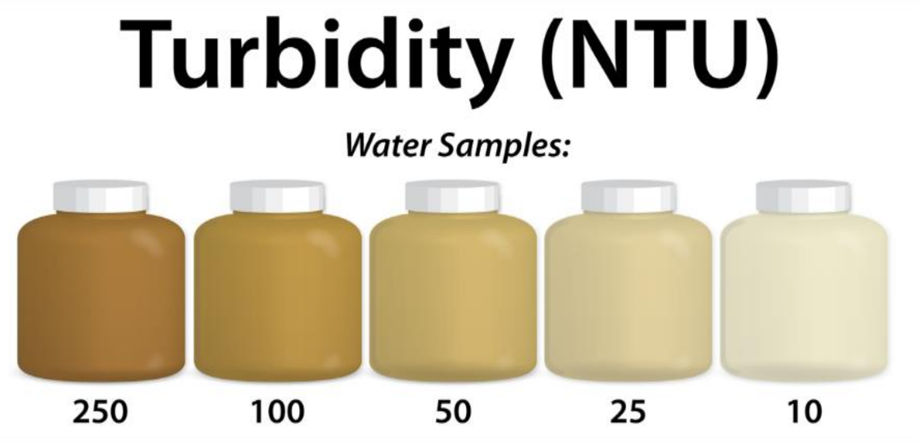
A. Physical Parameters

1. Suspended solids (big particles)
2. Turbidity (tiny particles)
3. Odor and Taste
4. Color
5. Temperature.

<u>1. Suspended solids (big particles)</u>

- Organic and inorganic particles in water are generally termed *total suspended solids (TSS).*
- **<u>Imhoff cones</u>** are used to measure for settleable solids, which are larger than TSS.
- TSS are measured by **<u>filtering</u>** a water sample, drying and weighing the filter paper.

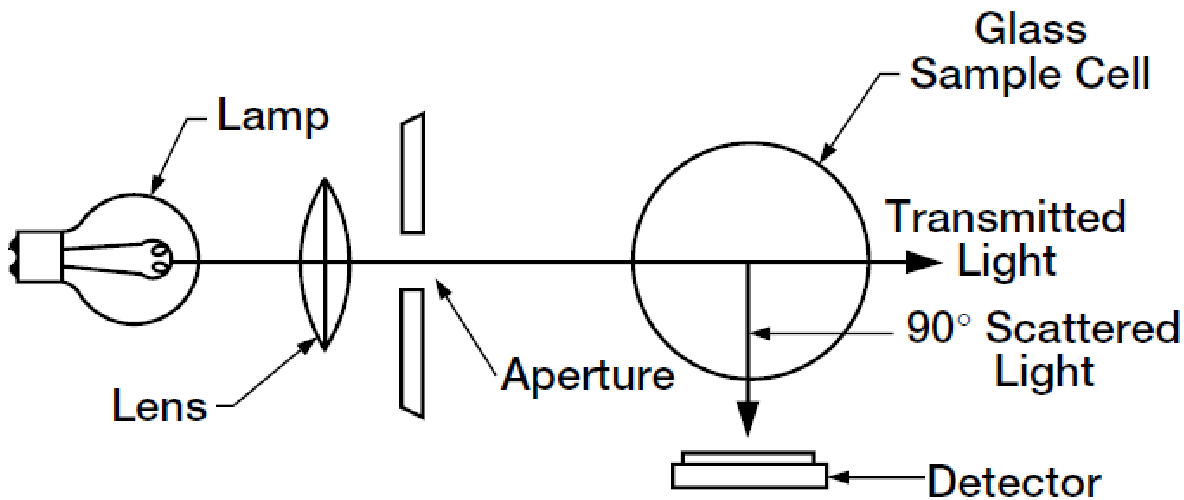
2. Turbidity



1. Used to assess the clarity of water
2. Due to *colloids* : particles that do not settle readily
3. When colloidal matter accumulates, light is scattered and the water appeared *turbid.*
4. Substances that cause turbidity include:
   - clay, silt,
   - tiny fragments of organic matter, and
   - microscopic organisms (e.g. bacteria, algae)

<u>Turbidity measurement:</u>

- measured in units that relate the clarity of the water sample to that of standardized suspension of silica (SiO_2).
- The interference in the passage of light caused by a suspension of 1 mg/l of silica is equivalent to <u>one</u> **turbidity units** (TU).
- Measurement: Nephelometers (NTU).



3. Odor

1. A physical characteristics of drinking water that is important for *aesthetic reasons.*
2. It may be caused by dissolved or suspended colloidal particles of *organic nature.*
3. It is measured by human panel or **electronic nose (olfactory device)** expressed in terms of a threshold odor number (TON).

TON: It is the ratio by which the sample has to be diluted for the odor to become virtually unnoticeable.

Example: 50 ml is diluted to vol. of 200 ml.

The dilution # equals 200/50 = 4 = TON

3. Taste

1. Taste is an aesthetic water quality parameter.
2. Caused by presence of organic and / or inorganic substances:

- Organics cause both odor & Taste problems.
- Inorganics (e.g. soil components) are usually odorless and *may* be responsible for taste.

Odor & Taste :

most commonly caused by:

algae, decomposed organic matter, and dissolved gases.

4. Color

- is a physical characteristics of drinking water that are important for esthetic reasons.
- It may be caused by dissolved or suspended colloidal particles.
- One color unit is equivalent to the color produced by a 1 mg/L solution of platinum (Pt).

5. Temperature

- Warm water tastes flat. Cooling suppresses odors and tastes and makes water more palatable.
- Temperature effects the chlorination and purification of water.
- Disinfection takes longer when water is colder
- At lower T, purification capacity is reduced with reverse osmosis treatment equipment.
- Water having physical characteristics exceeding the limits or making it less palatable should not, as a general rule, be used for drinking.

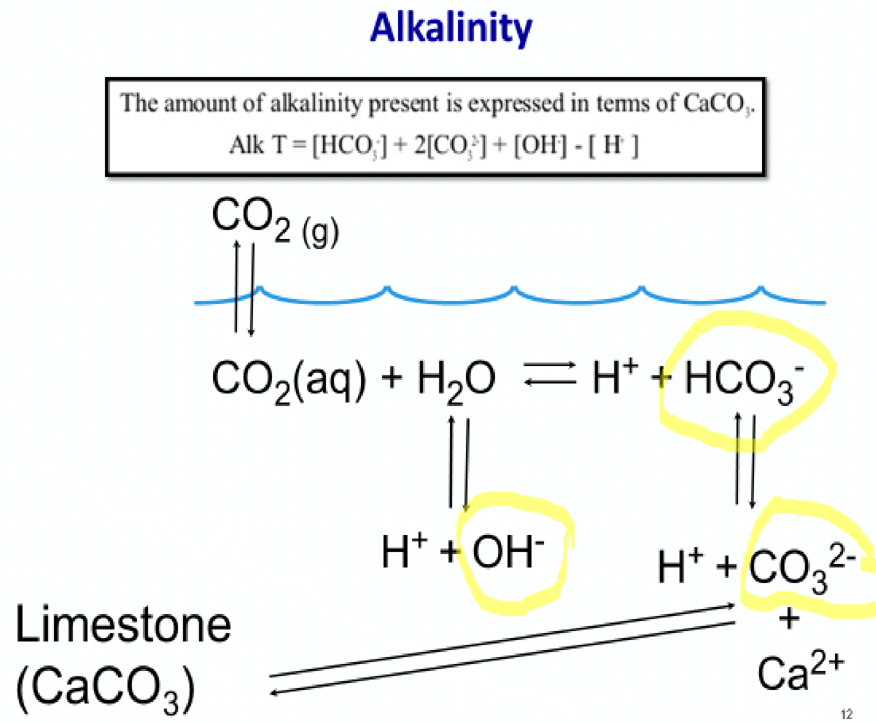
B. Chemical Parameters

Total dissolved solids:

- Alkalinity
- Hardness
- Fluoride
- Metal ions
- Organics
- Nutrients

ANALYSIS:

- *Gross: alkalinity, hardness.*
- *Specific ions: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, $NO3^{-}$, pH (H^{+} or OH^{-})*



Hardness

- Multivalent cations, particularly magnesium and calcium, causes the hardness.
- These ions are easily precipitated and form scales especially in heat transfer equipment and a problem arise up.
- Correlated with TDS (as part of it), they represent total concentration of Ca and Mg, and is reported in equivalent CaCO3 (mg/L).
- Other ions (Fe2+, Al3+) may also contribute to hardness.

Hard water problems:

  - leaves solid deposits in boilers, hot water pipes, heaters, …) and
  - They also react with soap and detergents requiring more soap or detergent and form a difficult–to-remove scum

Advantage: hard water is less corrosive than soft water.

$$Hardness, eq/m^3 = (Ca^{+2}) + (Mg^{+2})$$

Chemical Parameters

Hardness in Water

Degree of Hardness	p.p.m. as $CaCO_3$
Soft	0-75
Moderately Hard	75 - 150
Hard	150 - 300
Very hard	>300

C. Radioactive Parameters

(Primary MCLs)

Radionuclides

Radium 226	20 pCi/L	Beta particle and photon radioactivity	4 mrem/yr
Radium 228	20 pCi/L	Radon	300 pCi/L
Gross alpha particle activity	15 pCi/L	Uranium	20 μg/L

1 Ci = decay rate of 1 g Radium-226

(= decay of 3.7x10 10 atoms/s)

D. Microbiological Parameters

Figure 22-3a Environment, 5/e

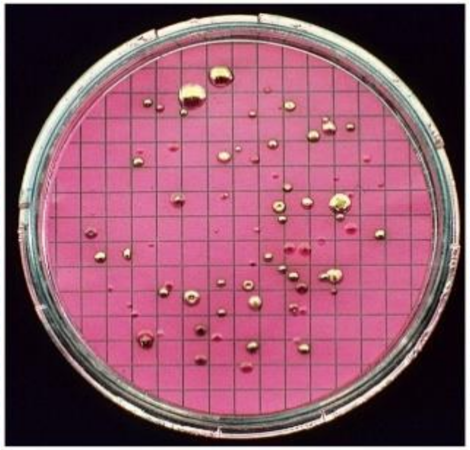


Figure 22-3b Environment, 5/e

Microorganisms:

1. Bacteria
2. Protozoa
3. Parasitic Worms
4. Viruses
5. Algae
6. Fungi
7. *Pollution indicators*: Coliform bacteria

❑ *E. coli* used as an indicator of water quality: normal inhabitant of intestines of humans and many animals.

- ✓Fecal Indicator Bacteria (FIB)
- ✓Indicator of presence of fecal matter
- ✓Total coliforms are typically reported

Microbiological Parameters

- A ***fecal coliform bacteria*** test is used to indicate the likely presence of disease-causing bacteria in water.
- Results reported as **Most Probable Number (MPN) per 100 mL.**
- Incubation at moderate temperature (35^{o}C) for 48 hr.

	MCL GOAL	MCL*
Total Coliforms (Including fecal coliforms & *E. coli*)	Zero	5%**
Viruses (Enteric)	Zero	99.99% killed or inactivated
Giardia lamblia	Zero	99.99% killed or inactivated

*MCL – Maximum Concentration Level
**No more than 5% of the water samples total coliform positive in a month. Every sample that has total coliforms must be analyzed for fecal coliforms. The presence of any fecal coliforms is unacceptable in drinking water.

Table 1. EPA National Drinking Water Regulations for Microorganisms.

Drinking Water Treatment

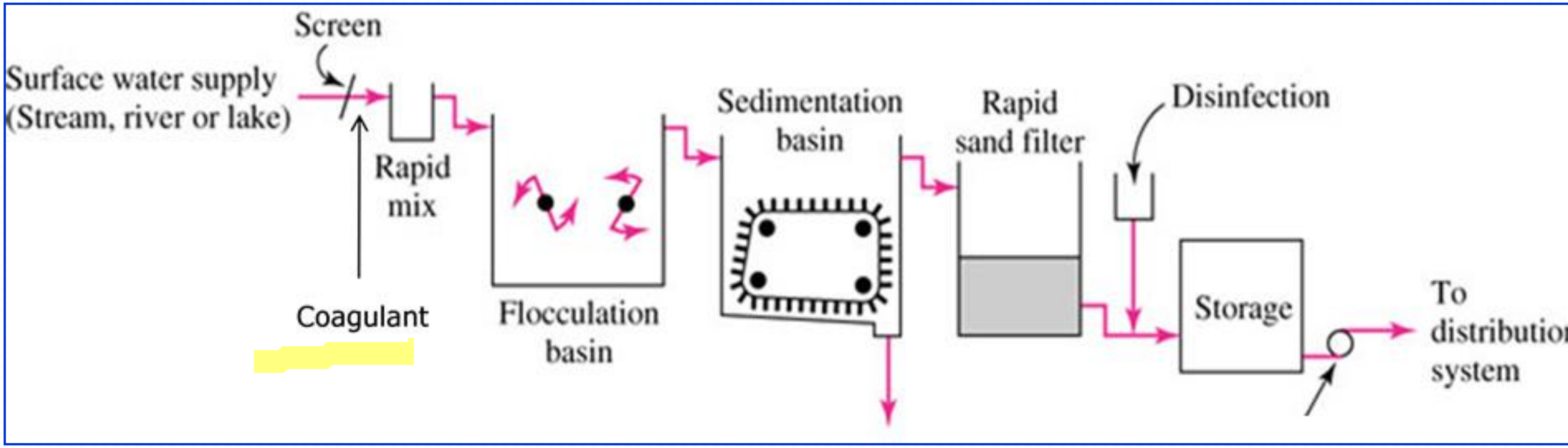
I. Surface Water Treatment

- **Primary objectives** are to
  1) Remove suspended material (turbidity) and color
  2) Eliminate pathogenic organisms
- Treatment technologies largely based on coagulation and flocculation

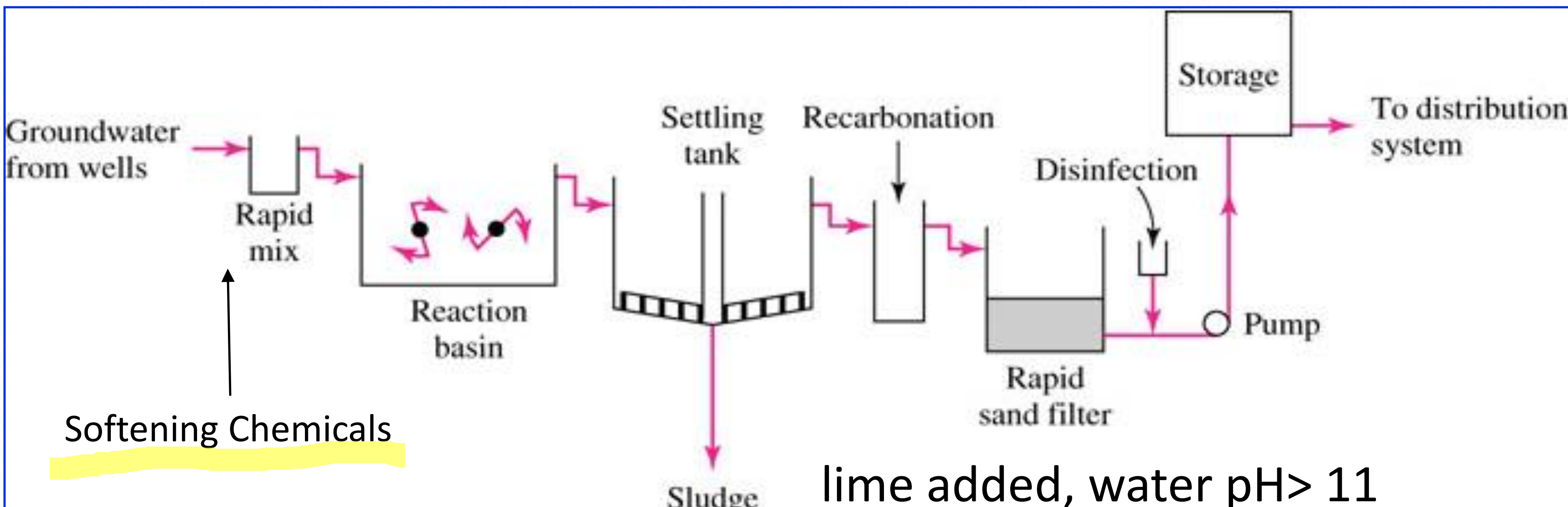
II. Groundwater Treatment

- **Primary objectives** are to
  1) Remove hardness and other minerals
  2) Eliminate pathogenic organisms
- Treatment technologies largely based on chemical precipitation

Surface Water Treatment



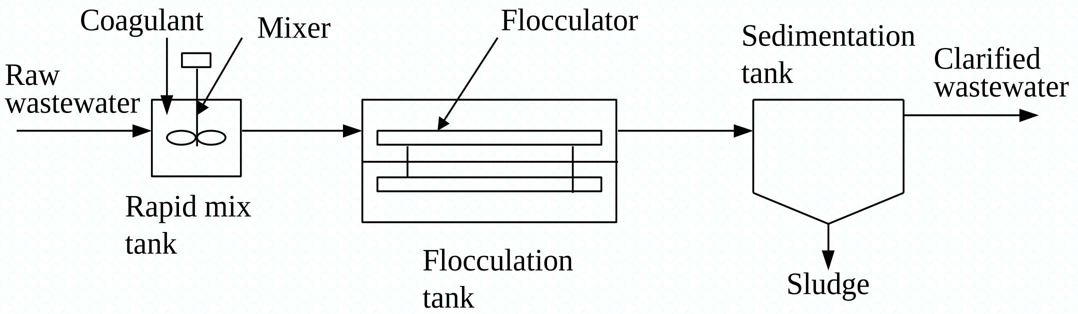
Groundwater Water Treatment



Surface Water Treatment

Removal of turbidity (and suspended solids formed):

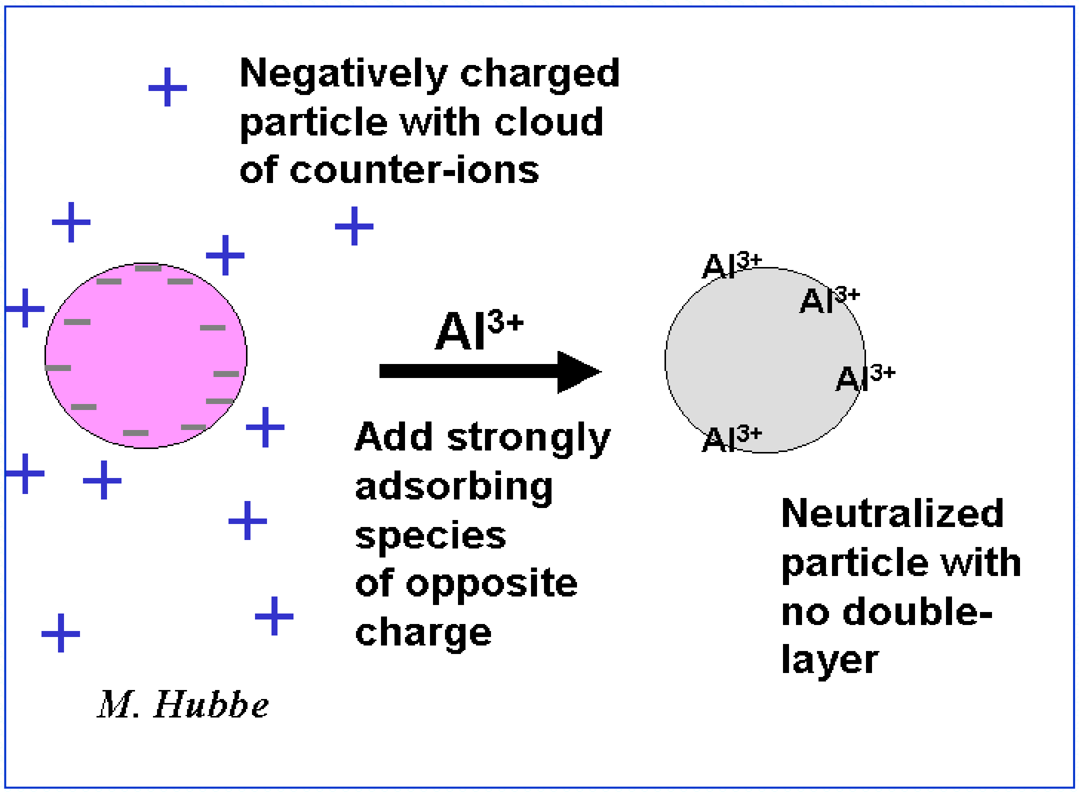
1. rapid mix (coagulation) tank
2. flocculation tanks
3. settling (sedimentation) tanks
4. Filtration

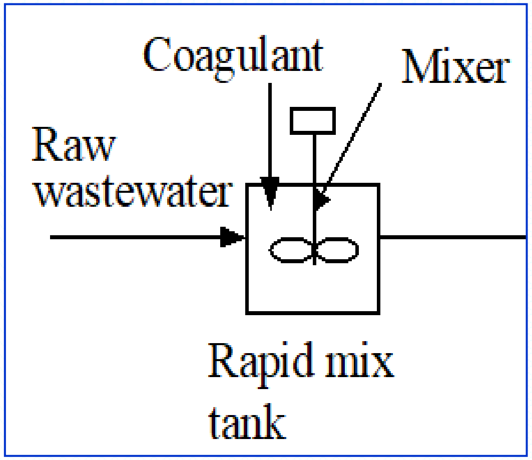


Coagulation

Addition and rapid mixing of a coagulant with the water to:

1) neutralize surface charges
2) collapse the (charged) surface layer around the particles
3) allow the particles to come together and agglomerate
4) allow the formation of floc that can readily settle





Good Coagulants

1) Non-toxic and relatively inexpensive
2) Insoluble in neutral pH range
3) Do not leave high concentrations of metals in treated water
4) Trivalent cations are most effective in charge neutralization.

Common Coagulants

- **Alum**
  - Hydrated aluminum sulfate [$Al_2(SO_4)_3 \cdot 14H_2O$]
  - Alum, when added to water, will be hydrolyzed to form gelatinous hydroxide [$Al(OH)_3$] precipitate.
  - This will carry suspended solids as it settles by gravity.
  - Optimum pH: 5.5 – 6.5.

- **Anhydrous Fe^{3+} (as $FeCl_3$)**
  - Forms $Fe(OH)_3$(s) in a wide range of pH 4-11, optimum 4.5 – 5.5.

Aluminum Chemistry

- With alum addition, what happens to water pH?

$$Al_2(SO4)_3.14\ H_2O \Leftrightarrow 2Al(OH)_3\downarrow + 8H_2O + 3H_2SO_4$$

- 1 mole of alum consumes 6 moles of bicarbonate (HCO_3^-)

$$Al_2(SO4)_3.14\ H_2O + 6HCO_3^- \Leftrightarrow 2Al(OH)_3\downarrow + 6CO_2 + 14H_2O + 3SO_4^{-2}$$

- If alkalinity is not enough, pH will be reduced greatly

$$Al_2(SO_4)_3.14H_2O \leftrightarrow 2Al(OH)_3\downarrow + 3H_2SO_4{}^- + 14H_2O$$

- Lime or sodium carbonate may be needed to neutralize the acid.

Iron Chemistry

$$FeCl_3 + 3HCO_3^- \Leftrightarrow Fe(OH)_3\downarrow + 3CO_2 + 3Cl^-$$

- With iron salt addition, what happens to water pH:
  1 mole of $FeCl_3$ consumes 3 moles of bicarbonate (HCO_3^-)
- If alkalinity is not enough, pH will reduce greatly due to hydrochloric acid HCl formation.
- Lime or sodium carbonate may be needed to neutralize the acid. Lime is the cheapest.

Flocculation

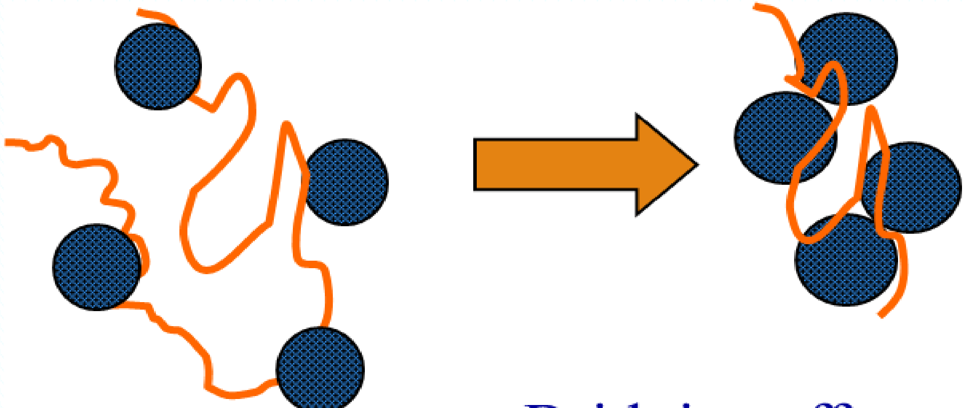
- The process that leads to the formation of large voluminous flocs, which are loosely held aggregates of coagulated particles and solids.

- The slow mixing is one of the fundamentals necessary to promote collisions between particles to form flocs.

Flocculation Chemical (Coagulant-Aids):

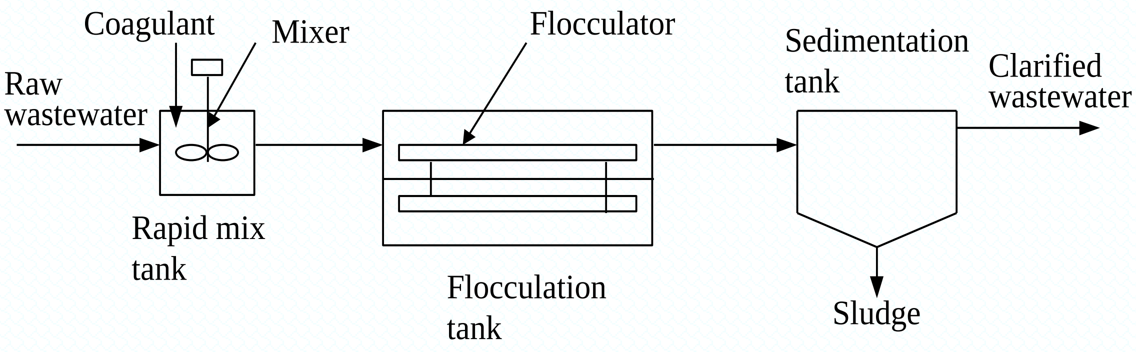
1. inorganic: polyaluminum chloride

2. Synthetic Polymers (Polyelectrolytes): polyacrylic acid, polyacrylamide derivatives



Bridging effect

Mixing & Flocculation Units



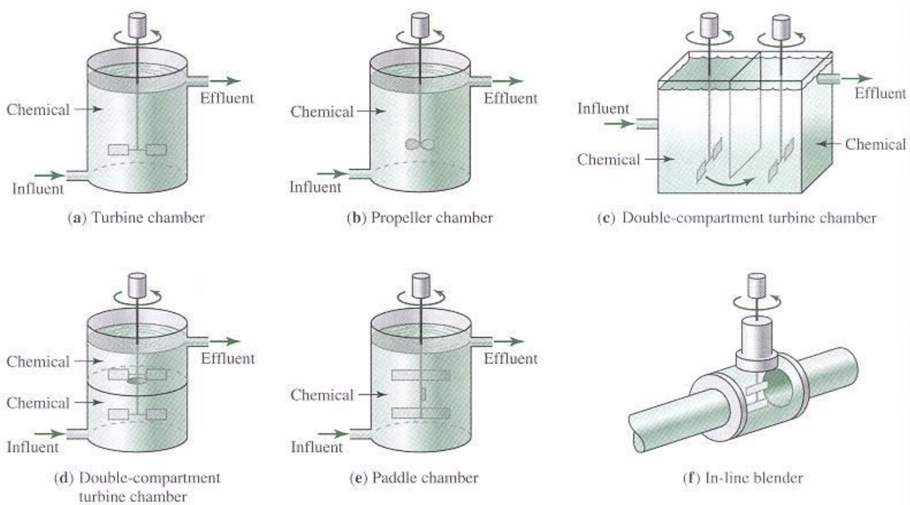


FIGURE 9–7

Paddle flocculator.

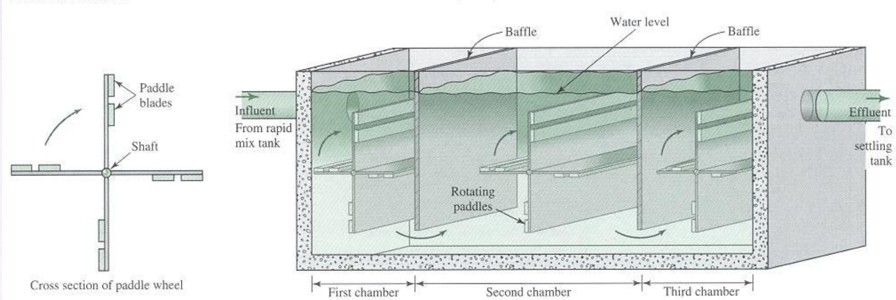
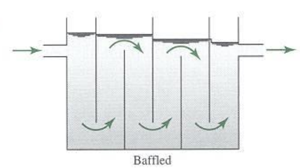


FIGURE 9–8

Baffled chamber flocculator.



Jar Test
Determining Coagulant Dose & Optimum pH

- The jar test – a laboratory procedure to determine the optimum pH and the optimum coagulant dose
- A jar test simulates the coagulation and flocculation processes

Jar Test set-up

Jar Test

determining optimum pH

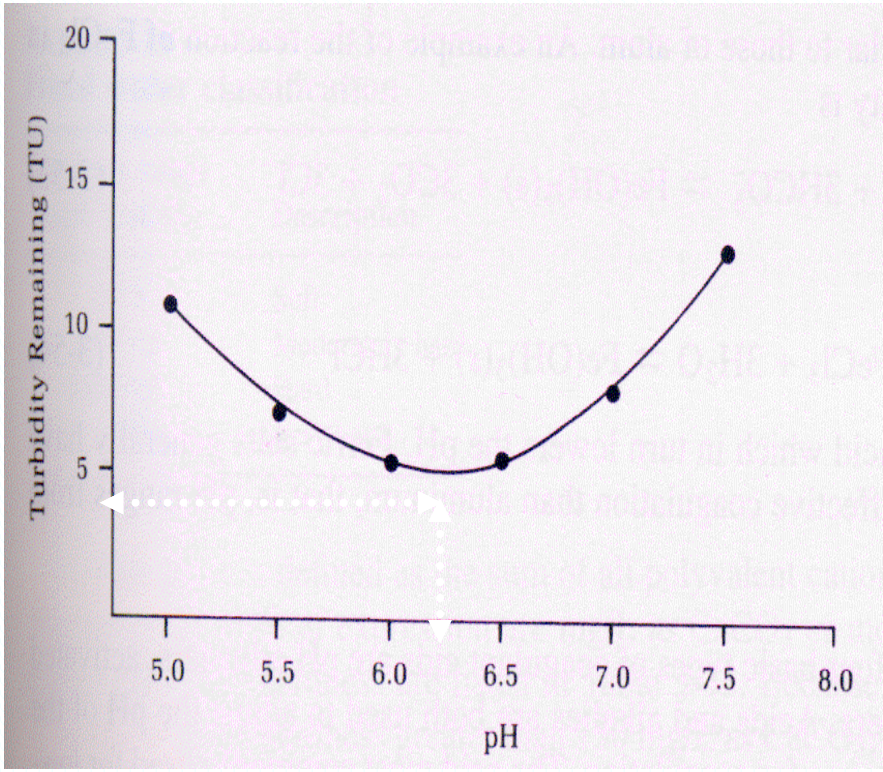
- Fill the jars with raw water sample – usually 6 jars
- Adjust pH while mixing using H_2SO_4 or NaOH (pH: 5.0; 5.5; 6.0; 6.5; 7.0; 7.5)
- Add same dose of selected coagulant to each jar (Coagulant dose: 5 or 10 mg/L)
- **Rapid mix** each jar at 100 to 150 rpm for 1 minute.
- **Reduce the stirring speed** to 25 to 30 rpm and continue mixing for 15 to 20 min.
- Turn off mixers and allow flocs to **settle** for 30 to 45 mins
- Measure the final residual turbidity in each jar
- Plot residual turbidity against pH.

Optimum coagulant dose

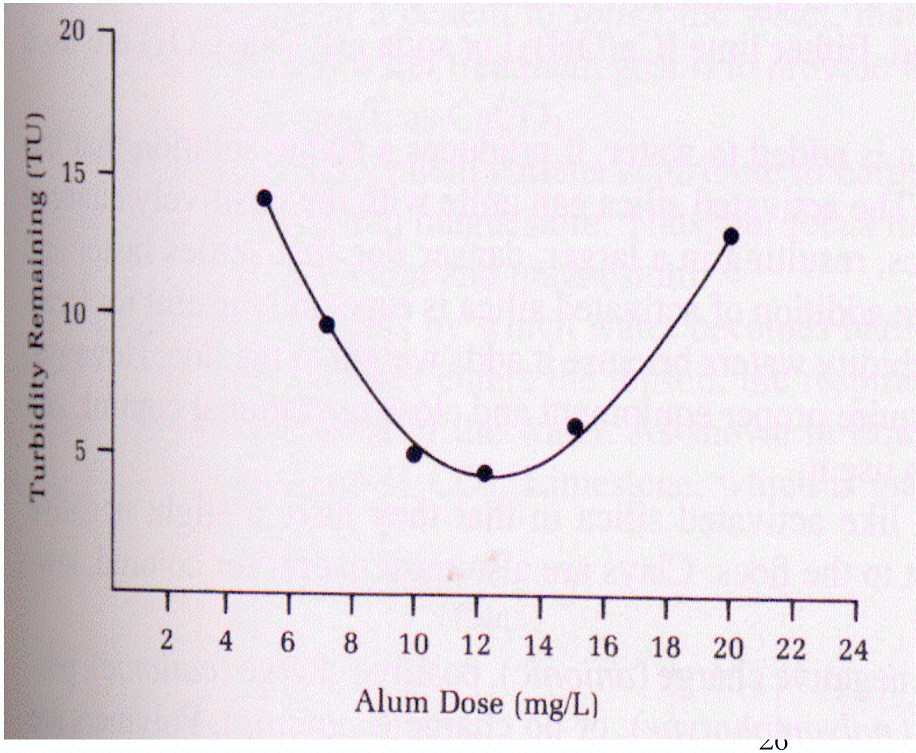
- Repeat all the previous steps
- This time adjust pH of all jars at optimum found from first test while mixing using H_2SO_4 or NaOH
- Add different doses of the selected coagulant (alum or iron) to each jar (Coagulant dose: 5; 7; 10; 12; 15; 20 mg/L)
- Rapid mix each jar at 100 to 150 rpm for 1 minute.
- **Reduce the stirring speed** to 25 to 30 rpm for 15 to 20 mins
- Turn off the mixers and allow flocs to **settle** for 30 to 45 mins
- Measure the final residual turbidity in each jar
- Plot residual turbidity against coagulant dose.

Coagulation Jar Tests

Jar Test – optimum pH



Jar Test – optimum dose



Coagulation / Flocculation Calculations

Measuring the degree of mixing

Velocity gradient: $$G = \sqrt{P/(\mu V)}$$

P = power input (W)
V = volume of basin(cu. m)
μ = fluid viscosity (Pa.s)

G values for rapid mixing

Detention time, t_0 (s)	G (s^{-1})
0.5	3500
10 – 20	1000
20 – 30	900
30 – 40	800
Longer	700

Gt_0 values for flocculation

Type	G (s^{-1})	Gt_0
Low turbidity, color removal coagulation	20 – 70	60,000 – 200,000
High turbidity, solids removal coagulation	50 - 150	90,000 – 180,000
Softening, 10% solids	130 - 200	200,000 – 250,000
Softening, 39% solids	150 - 300	390,000 – 400,000

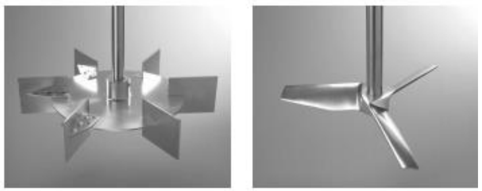
Coagulation / Flocculation Calculations

Designing a flocculator

Power input:

$$P = \frac{K_T (n)^3 (D_i)^5 \rho}{g}$$

K_T = impeller constant
n = rotational speed (rpm)
Di = impeller dia (m)



(a) Radial-flow turbine impeller (b) Axial-flow impeller

FIGURE 6-23
Basic impeller styles. (*Source:* Courtesy of SPX Process Equipment.)

Values of impeller constant K_T

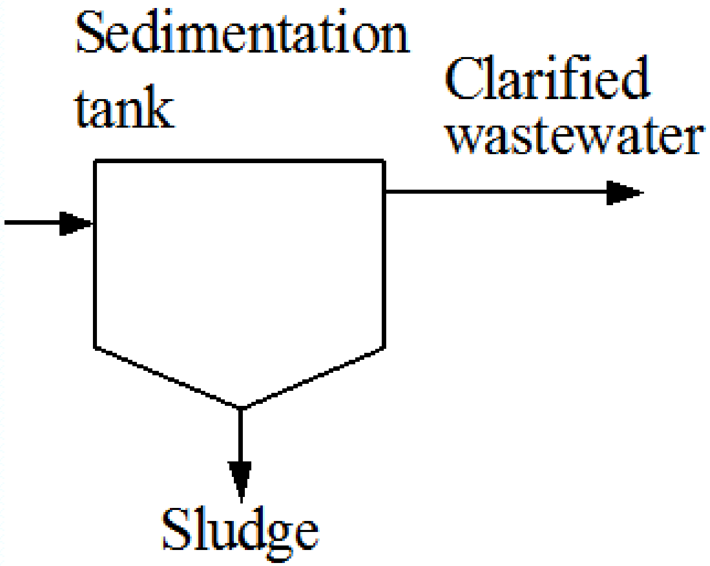
Type of impeller	K_T
Propeller, pitch of 1, 3 blades	0.32
Propeller, pitch of 2, 3 blades	1.00
Turbine, 6 flat blades, vaned disc	6.30
Turbine, 6 curved blades	4.80
Fan turbine, 6 blades at 45°	1.65
Shrouded turbine, 6 curved blades	1.08
Shrouded turbine, with stator, no baffles	1.12

Power and rotational speed of some standard mixers

Model	n (rpm)	P (kW)
JTQ50	30, 45	0.37
JTQ75	45, 70	0.56
JTQ100	45, 110	0.75
JTQ150	45, 110	1.12
JTQ200	70, 110	1.50
JTQ300	110, 175	2.24
JTQ500	175	3.74

JWI, Inc. of Holland

2. Sedimentation:



- Flocs settle out and is scraped and vacuumed off the bed of large sedimentation tanks.
- Clarified water drains out of the top of these tanks in a giant decanting process.

(For settling tank design and details, refer to Pre-requisite course notes (particulate separation).

3. Filtration

- ❑ Removal of those particles that are too small to be effectively removed during sedimentation.
- ❑ Sedimentation effluent: 1 - 10 JTU & Desired effluent level: <0.3 JTU
- ❑ Separate non-settleable solids from water. Combined with coagulation/ clarification, filtration can remove 84%-96% turbidity, over 97-99 Coliform bacteria and Giardia.

Slow sand filters AND Rapid sand filters

Either slow or rapid filtration (depends on size of plant / volume of water considerations).

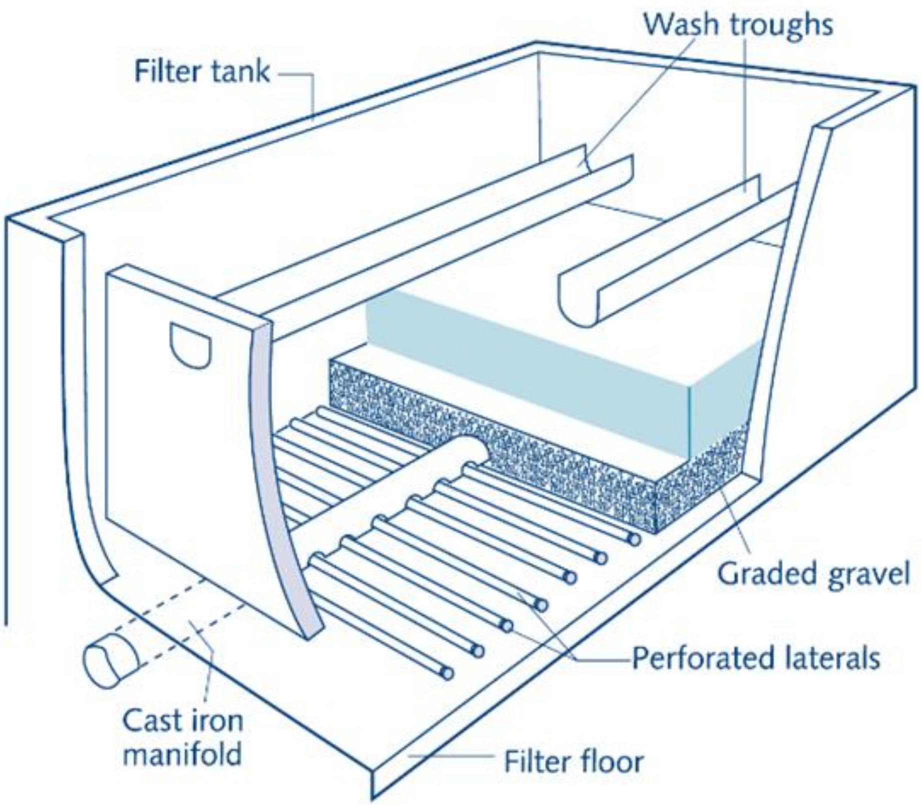
1) Rapid-sand filters

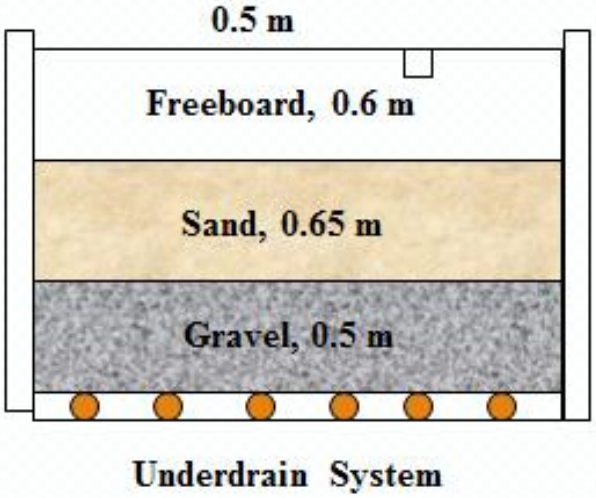
- force water through a 0.45-1 m layer of sand (d_p=0.4-1.2mm) and work faster, needing a smaller area. But they need frequent back-washing

3. Filtration

2) Slow-sand filters

(d_p=0.15-0.35mm) require a much larger area but reduce bacteriological and viral levels to a greater degree. The top 1 inch must be periodically scraped off and the filter occasionally back-washed

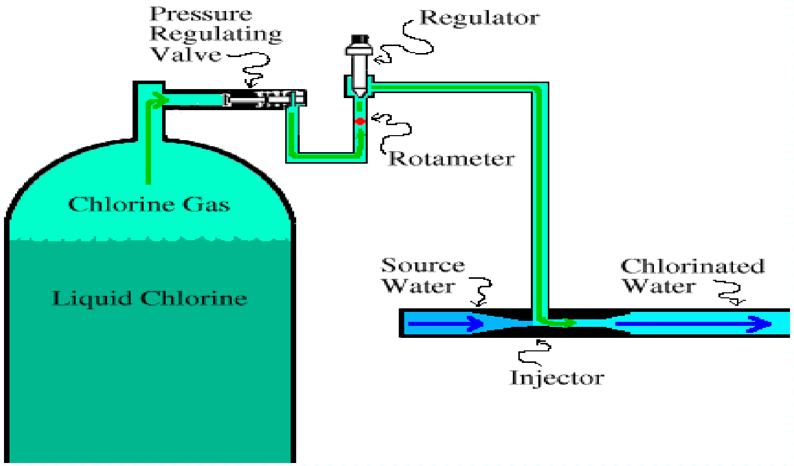




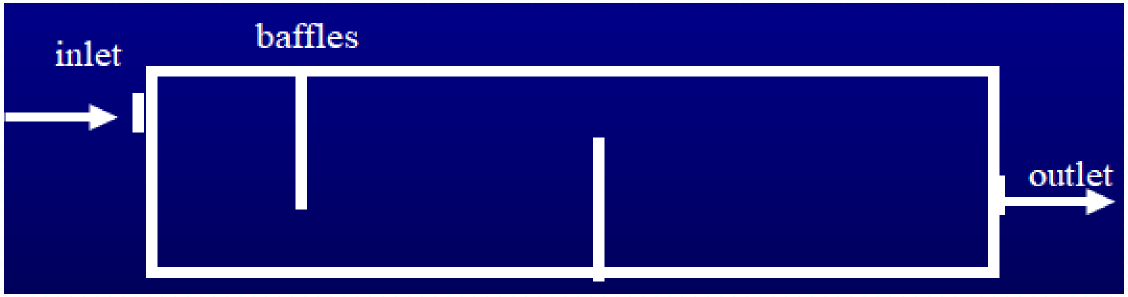
4. Disinfection:

1) Disinfection is typically the last step in a water (*and waste-water*) treatment system
2) Residual disinfectant is needed in distribution system after water (*or wastewater*) treatment
3) Water completely *free of suspended sediment* is treated with a powerful oxidizing agent usually chlorine gas.
4) A residual of chlorine disinfectant is left in the water to prevent reinfection. Chlorine can form *harmful byproducts* and has suspected links to stomach cancer and miscarriages. Many agencies now residually disinfect with Chloramine.
5) In addition to disinfection, chlorine also has the following functions:
    a. taste and odor control as an oxidizing agent
    b. oxidation of Fe^{2+} and Mn^{2+} in groundwater
    c. ammonium removal in domestic waste treatment
    d. slime, biofouling control

Disinfectants



1. Gaseous Cl_2
   - Most commonly used.
   - Advantage: provide residual chlorine for the protection from bacterial growth in distribution system
   - Disadvantage: The formation of disinfection by-products (trihalomethanes) presents a health risk
2. Hypochlorite: NaOCl or $Ca(OCl)_2$
3. Ozone: generated on site
4. UV lamps: for small applications.

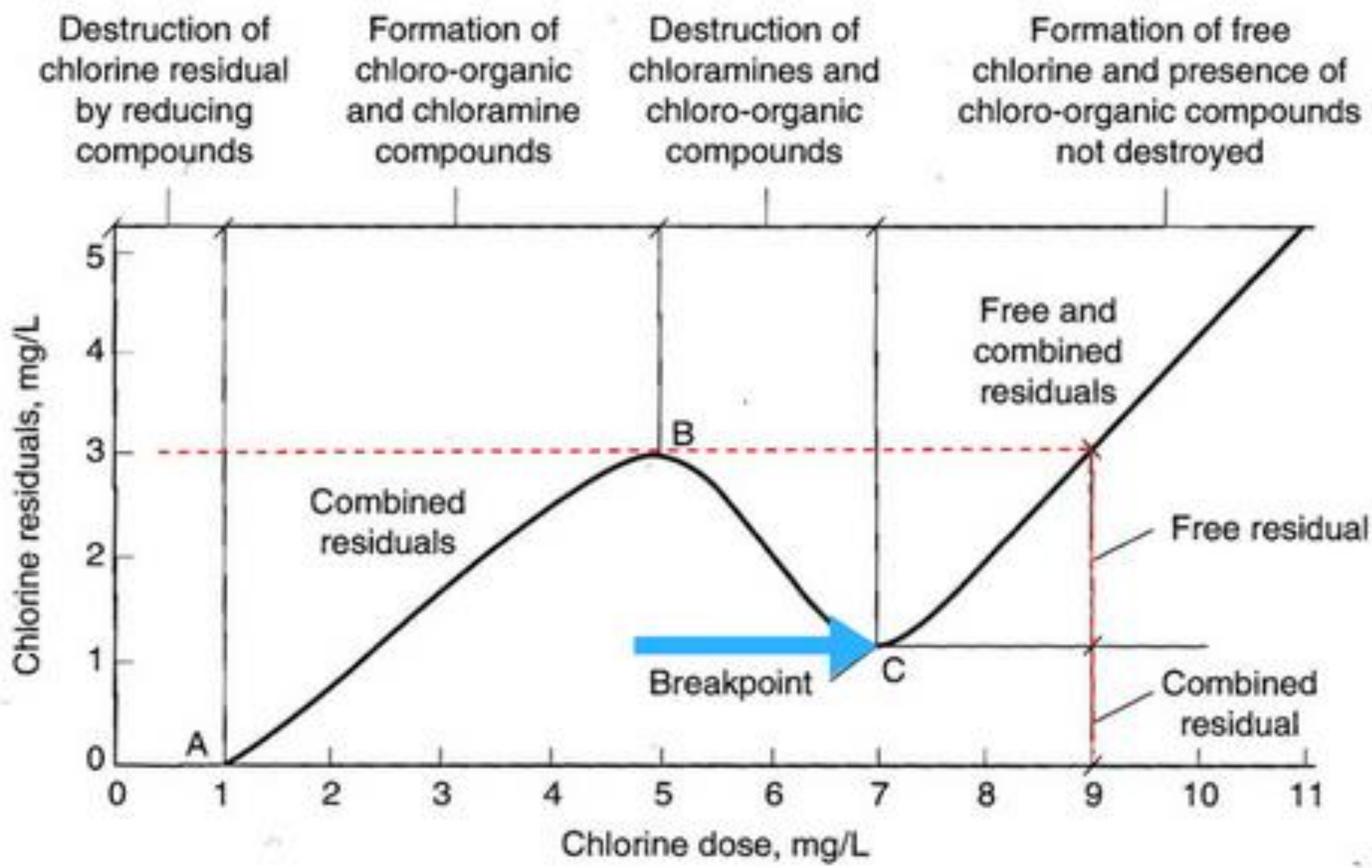


Chemistry of Chlorine in Water

$$Cl_2 + H_2O \rightarrow H^+ + Cl^- + HOCl$$

1. HOCl is a weak acid ($HOCl = H^+ + OCl^-$) with **K_a = 4.5x10^{-4}**
2. HOCl and OCl^- are free available chlorine which are very effective in killing bacteria
3. Small amount of ammonium (NH_4^+) in water is *desired* to form Chloramines: NH_2Cl, $NHCl_2$, NCl_3
   - *Chloramines (combined available chlorine) are weaker disinfectants than free available chlorine but are desired residual chlorine to be retained in water distribution system*
4. Excessive amount of ammonium (NH_4^+) in water is *undesirable* because it consume excess demand of Cl_2

Chlorine Demand or Breakpoint Chlorination



- Combined chlorine is the proportion that combines with organic matter.
- Free chlorine is the amount that remains to kill microbes in water system.
- Total chlorine is the sum of Combined and Free chlorine.

Disinfection CT* Concept

CT = 0.9847 C **0.1758 pH2.7519 temp**- 0.1467**

Inactivation is a function of __Contact time__, __Concentration__, __pH__, and __Temperature__.

To get credit for 99.9% inactivation of Gardia microorganism:

Contact Time (min)

chlorine	pH 6.5		pH 7.5	
(mg/L)	**2°C**	**10°C**	**2°C**	**10°C**
0.5	300	178	430	254
1.0	159	94	228	134

***CT: Concentration** (mg/L) **x Contact Time** (minutes)

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2. Peavy, H.S.; D.R. Rowe and G. Tchobanoglous. Environmental Engineering, McGraw-Hill, 1985.
3. Parsons, S. and Jefferson, B. Introduction to Potable Water Treatment Processes, Wiley-Blackwell, 2006.
4. Spellman, F.R. and Drinan, J.E. The Drinking Water Handbook, 2nd Edition, CRC Press, 2012.

Exercise-1

Example 6-2. Given the following analysis of a groundwater, construct a bar chart of the constituents, expressed as $CaCO_3$.

Ion	mg/L as ion	EW $CaCO_3$/EW ion	mg/L as $CaCO_3$
Ca^{2+}	103	2.50	258
Mg^{2+}	5.5	4.12	23
Na^{+}	16	2.18	35
HCO_3^-	255	0.82	209
SO_4^{2-}	49	1.04	51
Cl^-	37	1.41	52

Solution. The concentrations of the ions have been converted to $CaCO_3$ equivalents. The results are plotted in Figure 6-11.

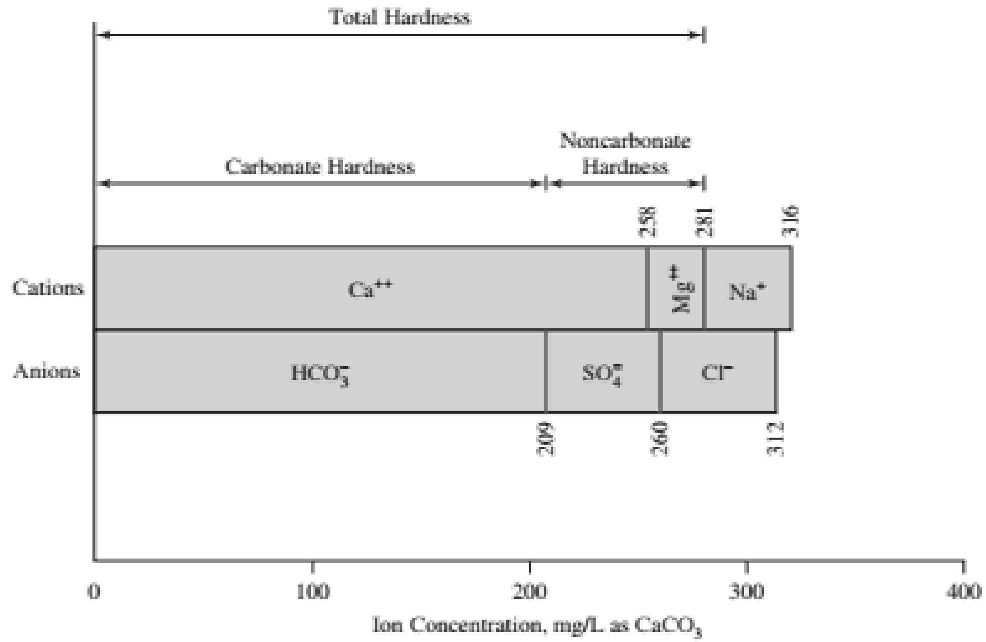


FIGURE 6-11
Bar graph of groundwater constituents.

Exercise-2

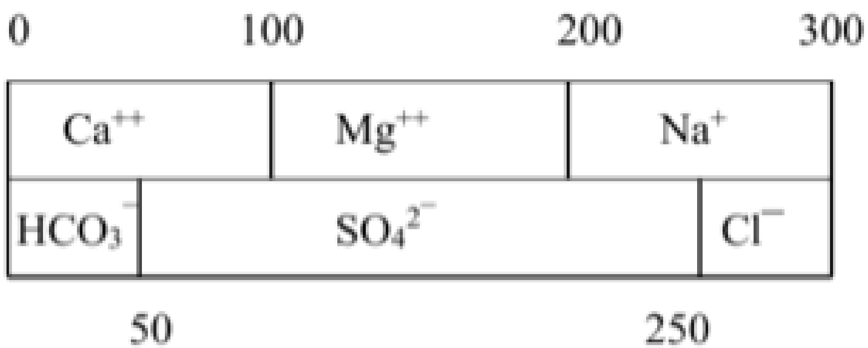
Given a water having the following composition:

Ca^{++} - 40 mg/L = 2 meq/L	HCO_3^- - 61 mg/L = 1 meq/L
Mg^{++} - 24 mg/L = 2 meq/L	SO_4^{2-} - 192 mg/L = 4 meq/L
Na^+ - 46 mg/l = 2 meq/L	Cl^- - 35.5 mg/L = 1 meq/L

These totals must balance

+ 6 meq/L   -6 meq/L

a) Put these in the form of a bar diagram expressing all concentrations in terms of $CaCO_3$ (50 mg/L $CaCO_3$ = 1 meq/L)



From ion to CaCO3:

Ca: 50/20 (or 100/40)
Mg: 50/12 (or 100/24)
Na: 50/23
HCO3: 50/61
SO4: 50/48 (or 100/96)
Cl: 50/35.5

From diagram you can see that

Total hardness = 200 mg/L as $CaCO_3$

Ca hardness = 100 mg/L as $CaCO_3$

Mg hardness = 100 mg/L as $CaCO_3$

Total alkalinity = bicarbonate alkalinity = 50 mg/L as $CaCO_3$ Why?

- **Carbonate Hardness (CH) = 50 mg/L as CaCO3**
- **Non-Carbonate Hardness (NCH) = TH – CH = 200-50 =150 mg/L as CaCO3**

Exercise-2

A surface water treatment plant is to process 30000 m^3/d for a large city. A cubic rapid mixing tank will be used to blend 35 mg/L of alum solution with the flow during a detention time of 2 minutes. The solution temperature is 22°C with a viscosity of 9.6×10^{-4} kg/m/s.

Determine the following:

a) Quantity of alum coagulant added (kg/day).
b) Tank dimensions.
c) Power input (kW) necessary for a velocity gradient (G) of 900 s^{-1}.

$$G = \sqrt{(P/\mu V)}$$

$$V = (Q).(t)$$