Water Treatment

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Drinking Water Treatment

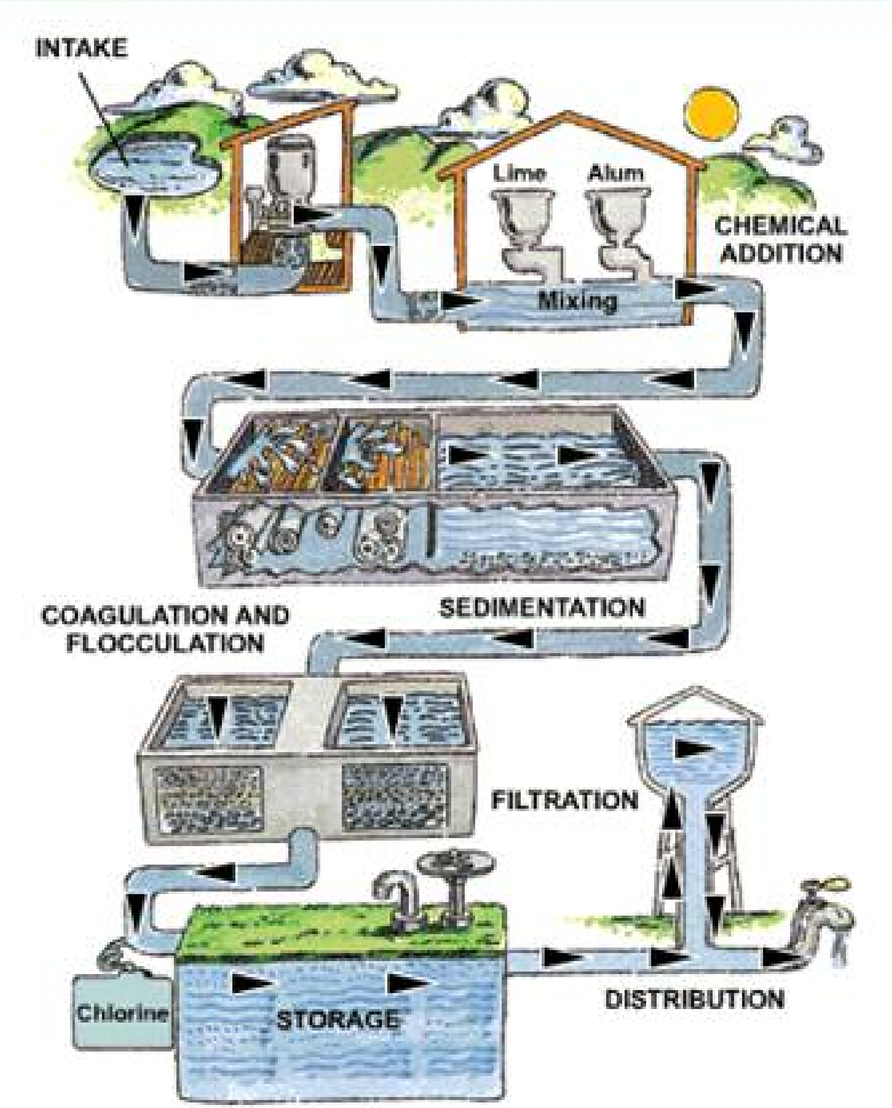
- It depends on the source: Surface or Ground Water

Surface Water Treatment

Primary objectives are to

- Remove suspended material (turbidity) and color
- Eliminate pathogenic organisms

➢ Treatment technologies largely based on **coagulation and flocculation**



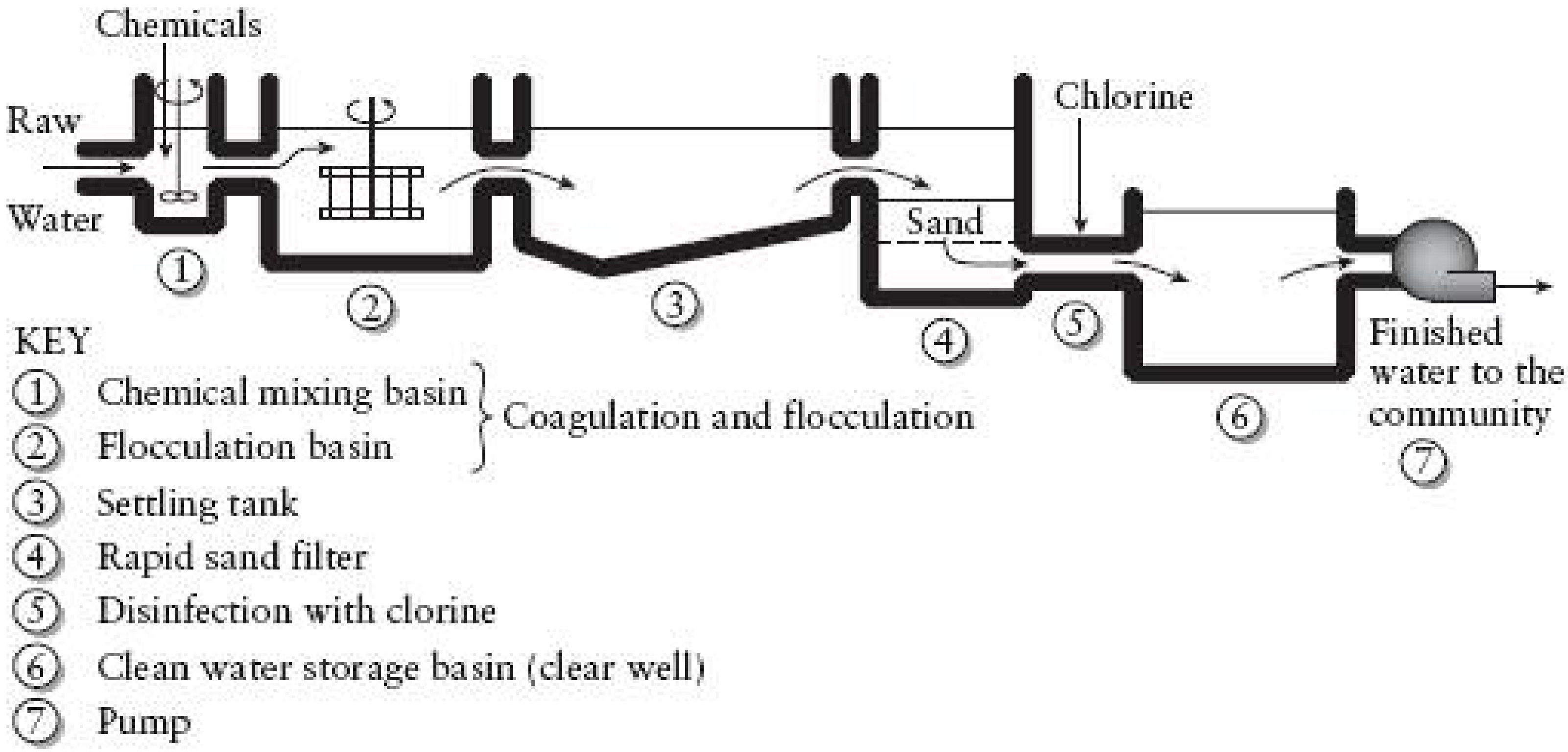
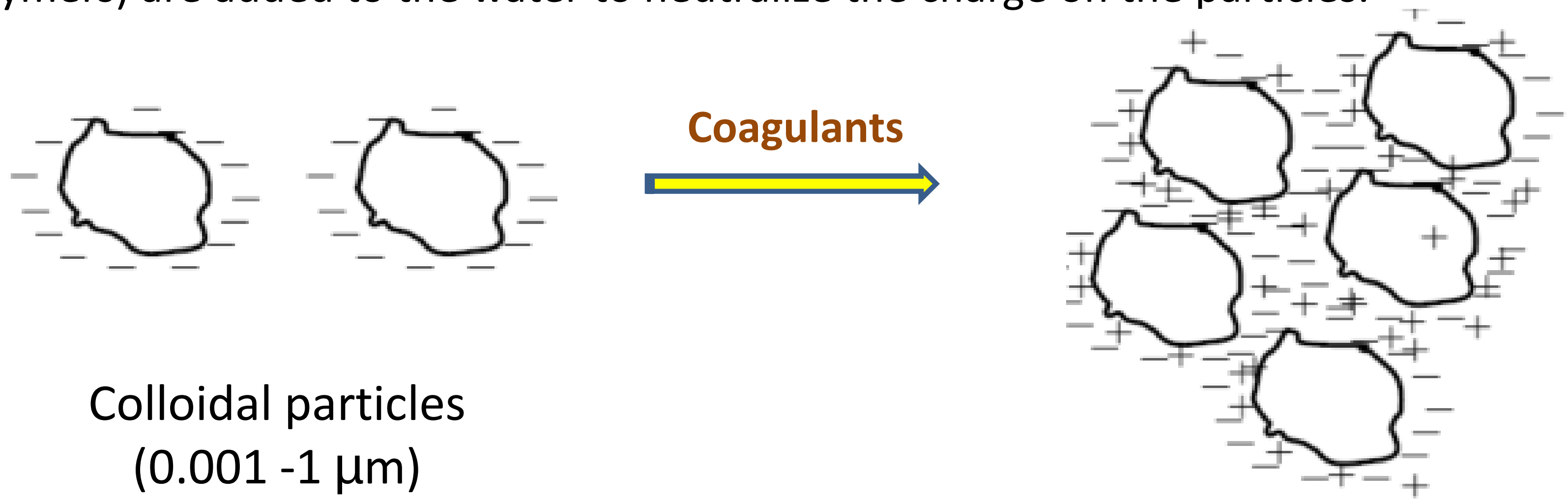


Figure 10.11 A typical water treatment plant.

Coagulation and Flocculation

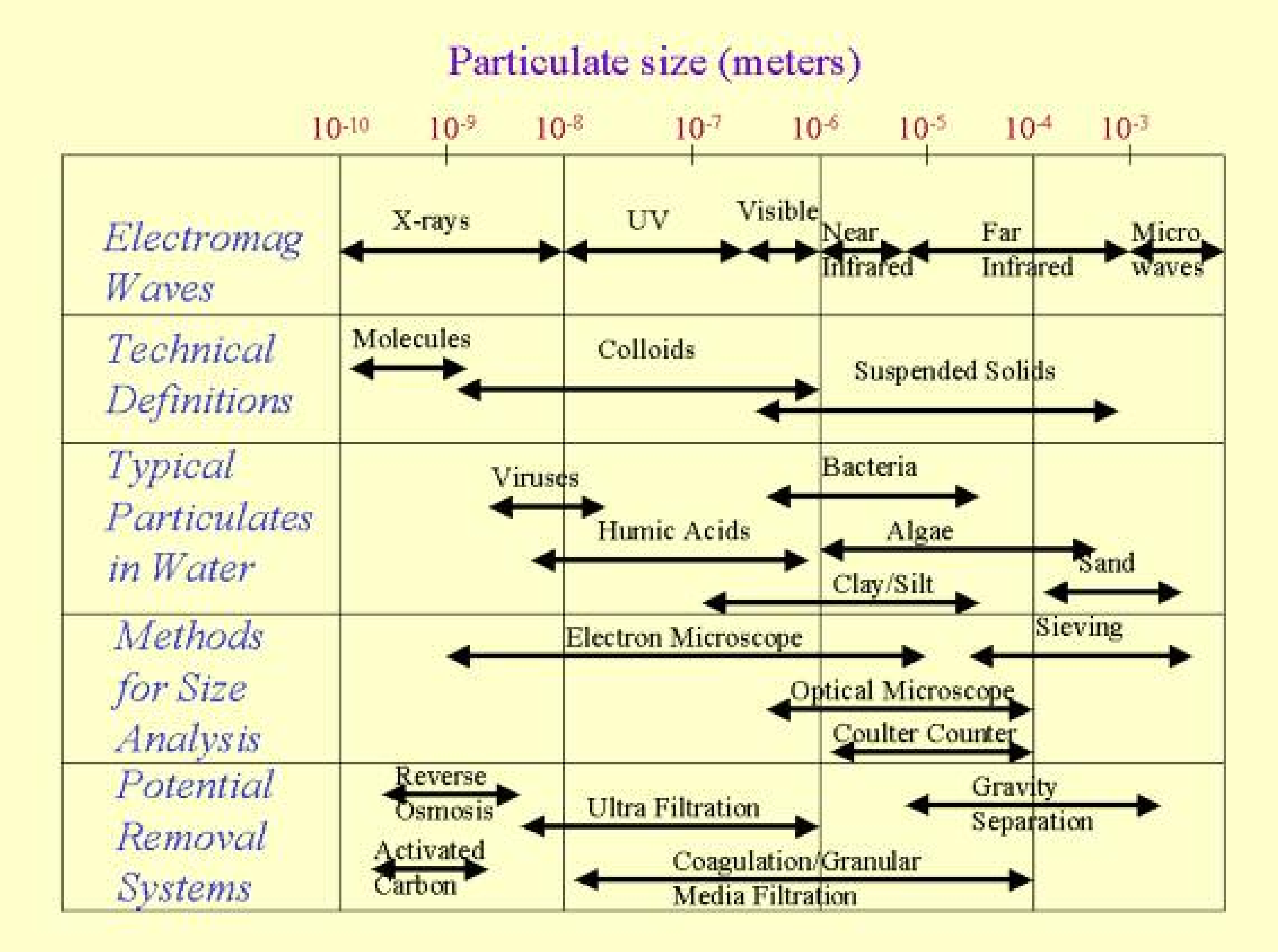
- ***Coagulation*** is the chemical alteration of the colloidal particles to make them stick together to form larger particles called ***flocs*** that readily settle.

- Tiny (colloidal) clay and silt particles: negative surface charge
- Particles repel so suspension is considered stable
- Coagulants (alum (aluminum sulfate), and coagulant aids, such as lime and polymers) are added to the water to neutralize the charge on the particles.



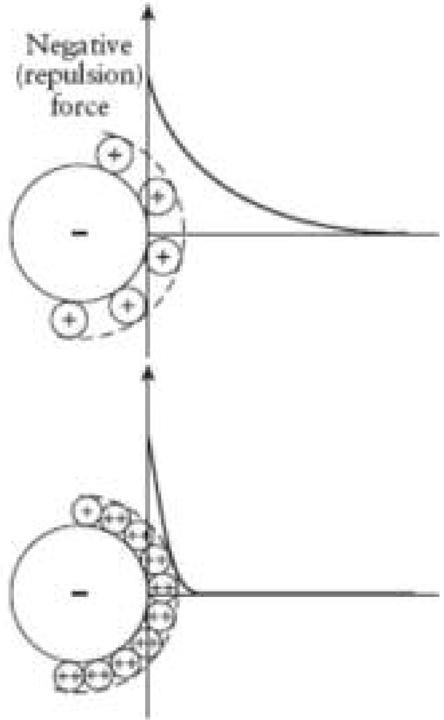
Colloidal particles
(0.001 -1 µm)

floc
(1 -100 µm)

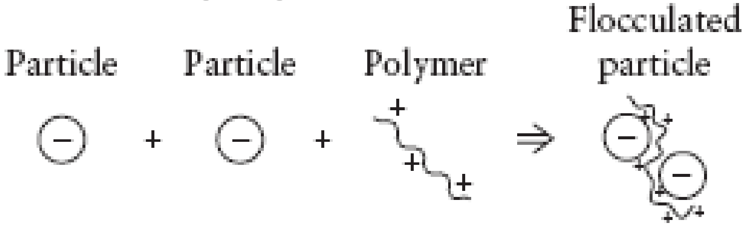

Particulate size (meters)
10-10
10-9
10-8
10-7
10-6
10-5
10-4
10-3
Electromag Waves
X-rays
UV
Visible
Near Infrared
Far Infrared
Micro waves
Technical Definitions
Molecules
Colloids
Suspended Solids
Typical Particulates in Water
Viruses
Bacteria
Humic Acids
Algae
Sand
Clay/Silt
Methods for Size Analysis
Electron Microscope
Sieving
Optical Microscope
Coulter Counter
Potential Removal Systems
Reverse Osmosis
Ultra Filtration
Gravity Separation
Activated Carbon
Coagulation/Granular Media Filtration

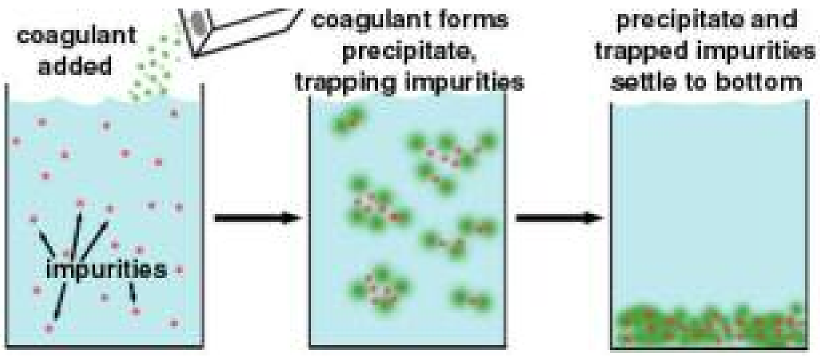
Coagulation: charge neutralization and bridging

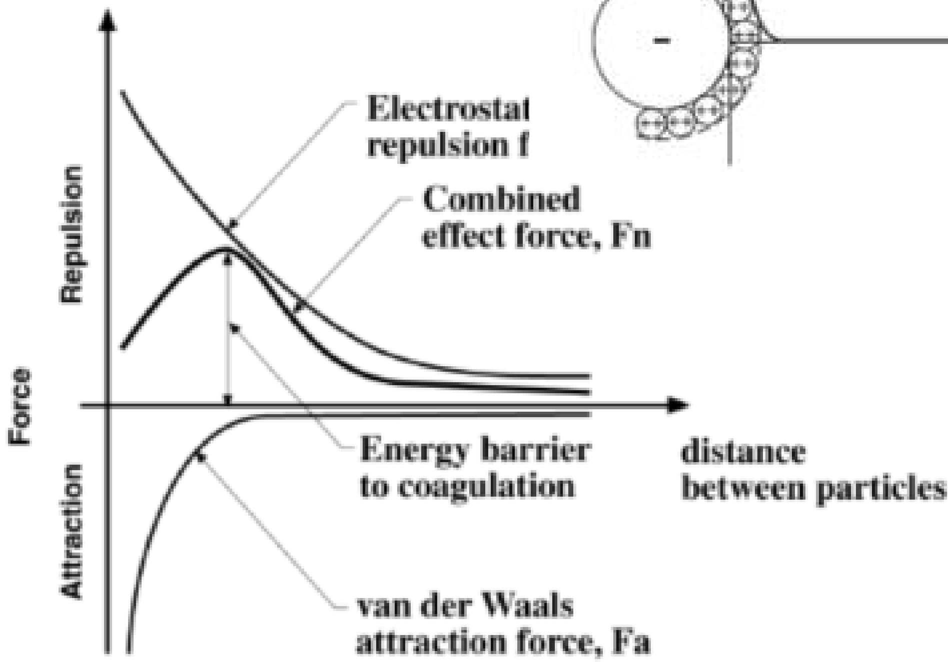
- **Charge neutralization:**
  - will cause instability and collision



- **Bridging**

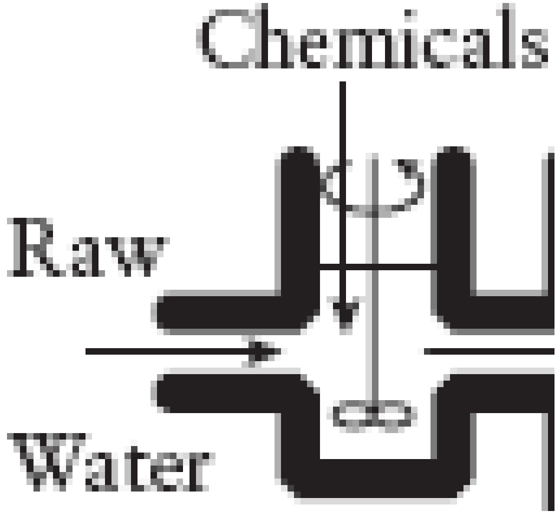






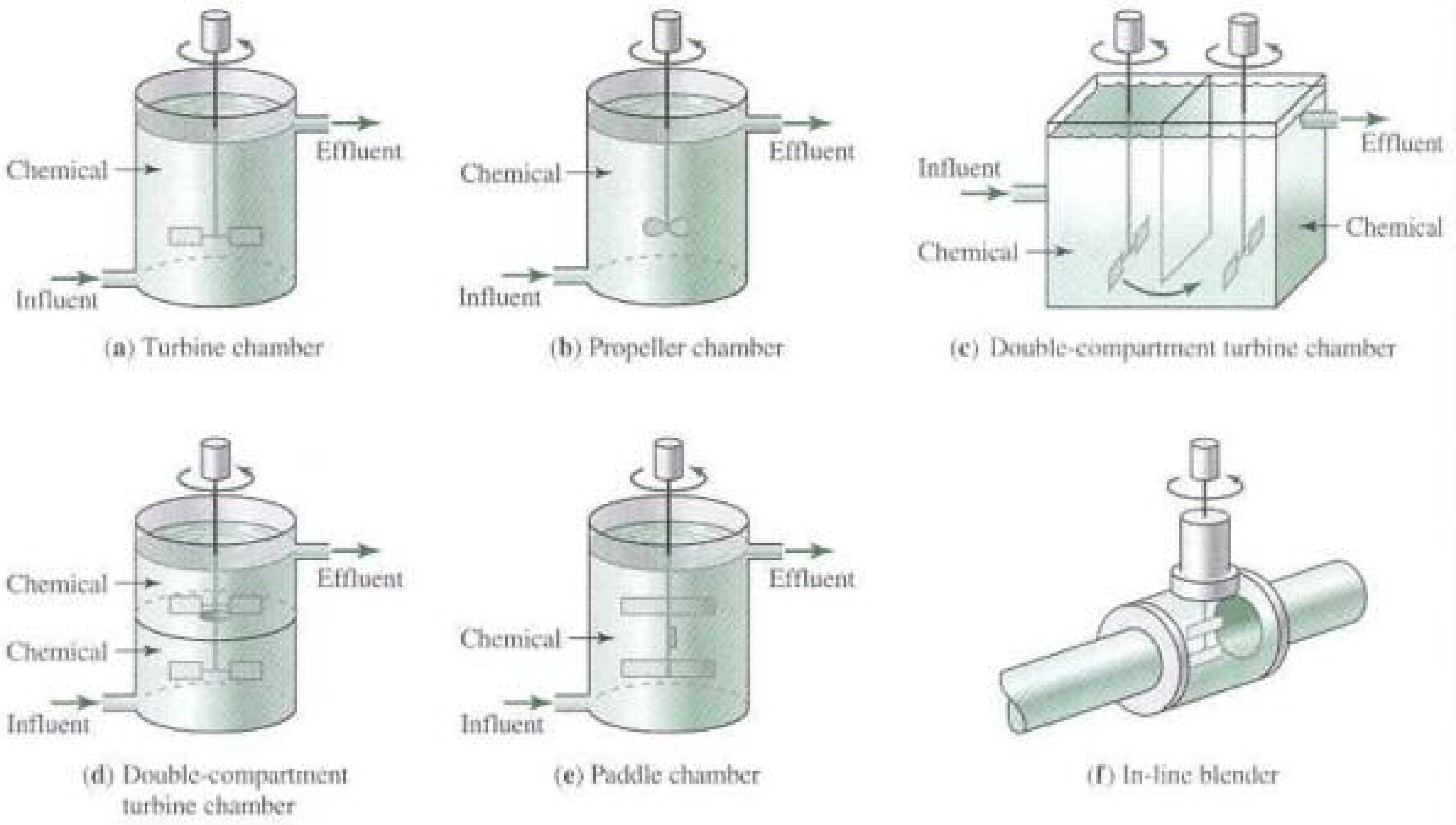
M.saidan

Rapid mixing



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

- ✓ neutralize surface charges
- ✓ collapse the surface layer around the particles
- ✓ allow the particles to come together and agglomerate
- ✓ allow formation of floc that can readily settle


Chemical
Effluent
Influent
(a) Turbine chamber
Chemical
Effluent
Influent
(b) Propeller chamber
Influent
Effluent
Chemical
Chemical
(c) Double-compartment turbine chamber
Chemical
Chemical
Effluent
Influent
(d) Double-compartment turbine chamber
Chemical
Effluent
Influent
(e) Paddle chamber
(f) In-line blender

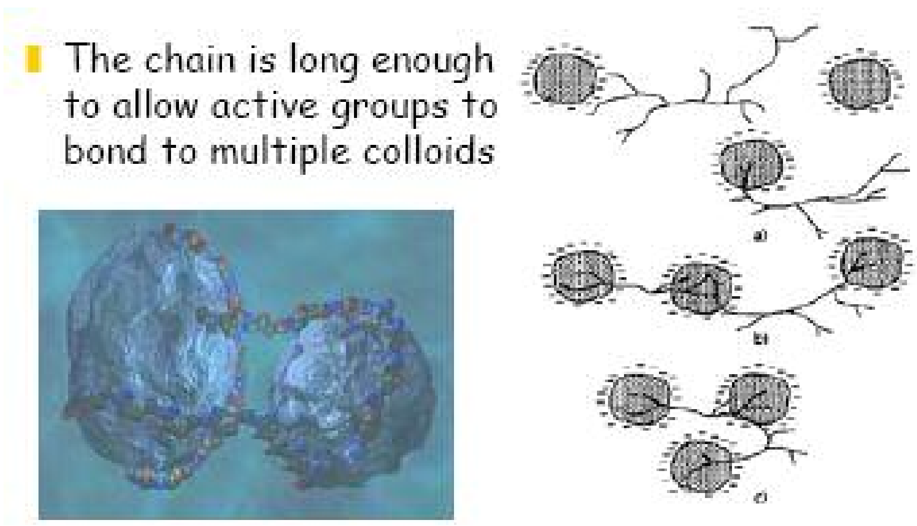
Coagulants: Non-toxic and relatively inexpensive

- **Alum**
  - ✓ Hydrated aluminum sulfate [$Al_2(SO_4)_3 \cdot 18H_2O$]
  - ✓ 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.
- **Anhydrous Fe^{3+}**
  - ➢ Forms $Fe(OH)_3(s)$ in a wide range of pH 4-11
- **Anhydrous Fe^{2+} ($FeSO4 \cdot 7H2O$)**
  - ➢ Must be oxidized to Fe^{3+} first at pH higher than 8.5
- **Coagulant Aids (Polyelectrolytes)**
  - ➢ Natural: Starch, cellulose derivatives, and gums (polysaccharides)
  - ➢ Synthetic polymers

Flocculation

- It is the agglomeration of destabilized particles into a large size particles known as flocs which can be effectively removed by sedimentation or flotation.

- It needs gentle mixing.
- To enhance the agglomeration, organic polymers (flocculent) are added.



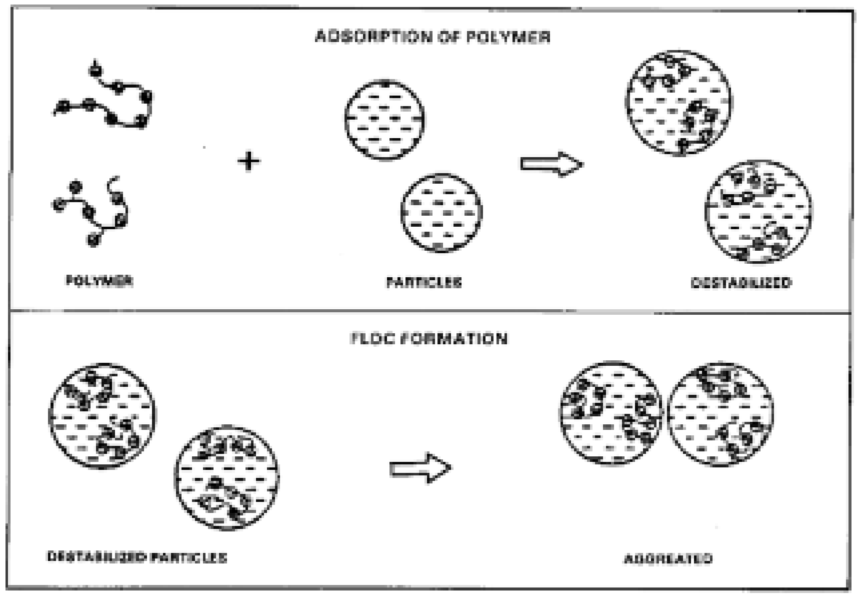
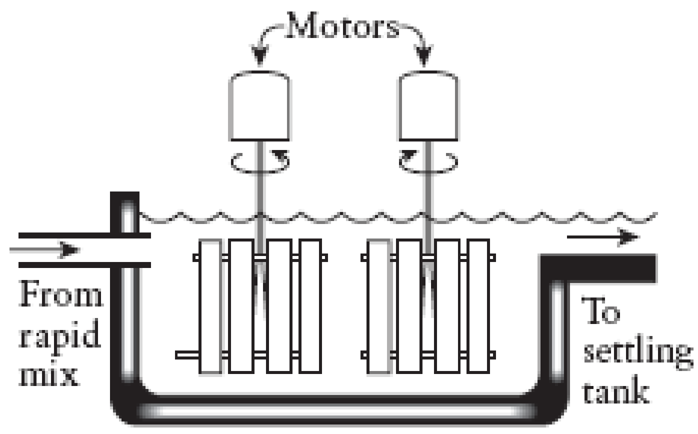


Figure 1-2. Floc formation process

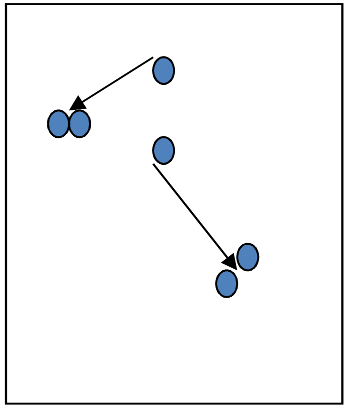
- The intent of the process of flocculation is to produce differential velocities within the water so that the particles can come into contact.



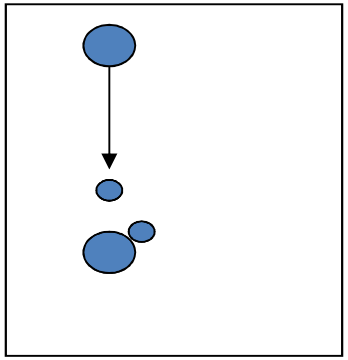
Typical flocculator used in water treatment.

Transport Mechanisms:

- ***Brownian motion***: for relatively small particles which follow random motion and collide with other particles (perikinetic motion)

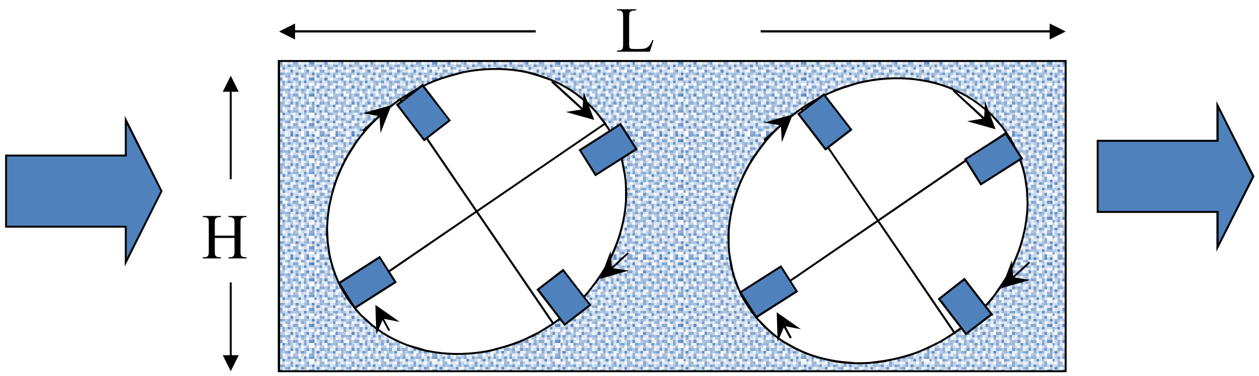


- ***Differential settling***: Particles with different settling velocities in the vertical alignment collide when one overtakes the other (orthokinetic motion)

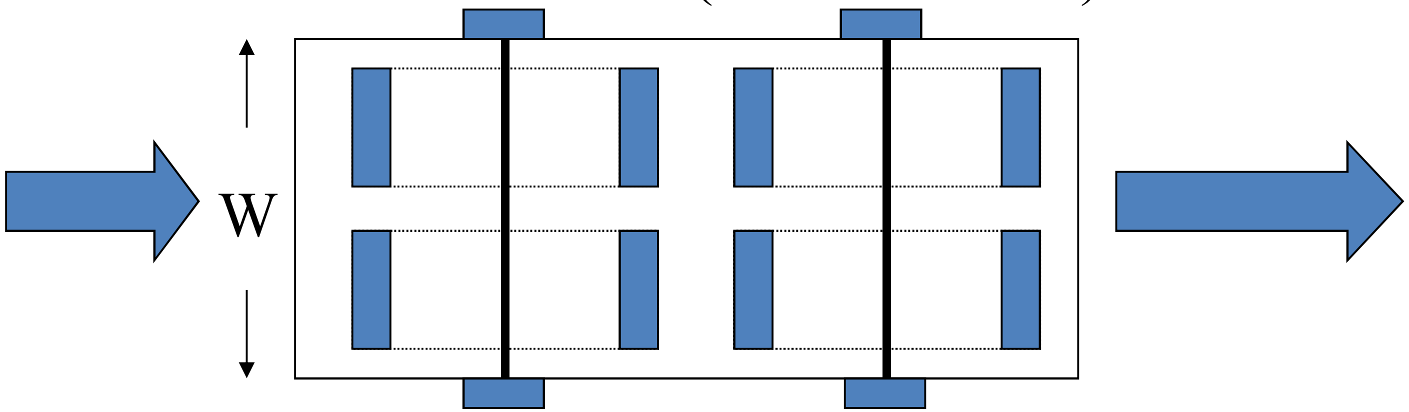


Mechanical Flocculator

Transverse paddle



Cross flow Flocculator (sectional view)

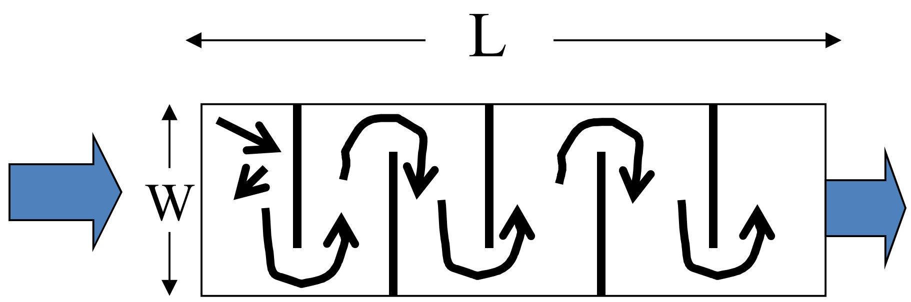


Plan (top view)

Hydraulic Flocculation

- *Horizontally baffled tank*

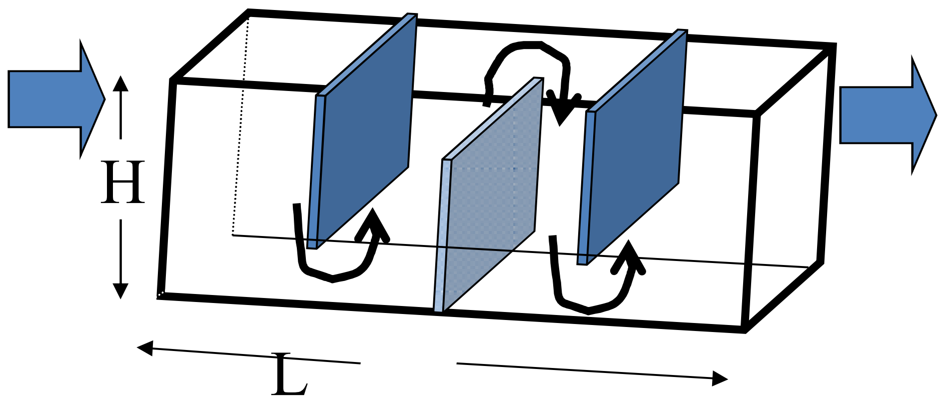
  The water flows horizontally.
  The baffle walls help to create turbulence and thus facilitate mixing



Plan view (horizontal flow)

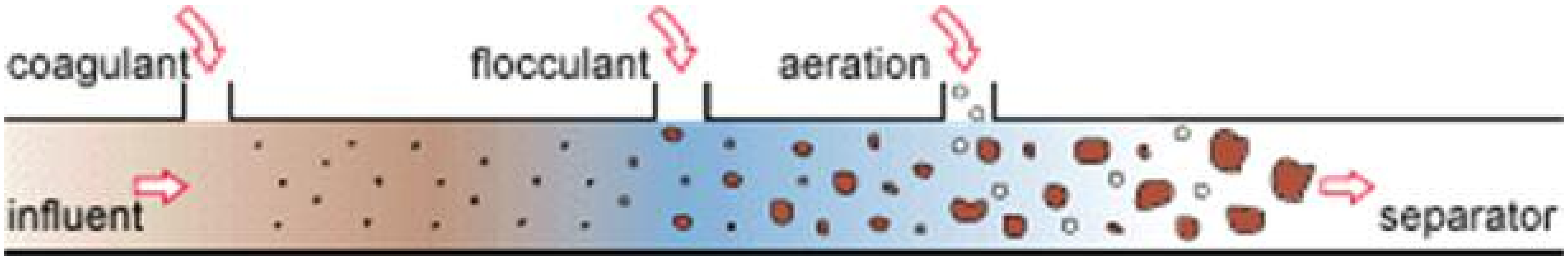
- *Vertically baffled tank*

  The water flows vertically. The baffle walls help to create turbulence and thus facilitate mixing



Isometric View (vertical flow)

Hydraulic Flocculation: Pipe



Flocculators integrated with settling

Flocculator perforated wall

Determining Coagulant Dose

Jar Tests

- 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

Determination of optimum pH

- Fill the jars with raw water sample (500 or 1000 mL) – usually 6 jars

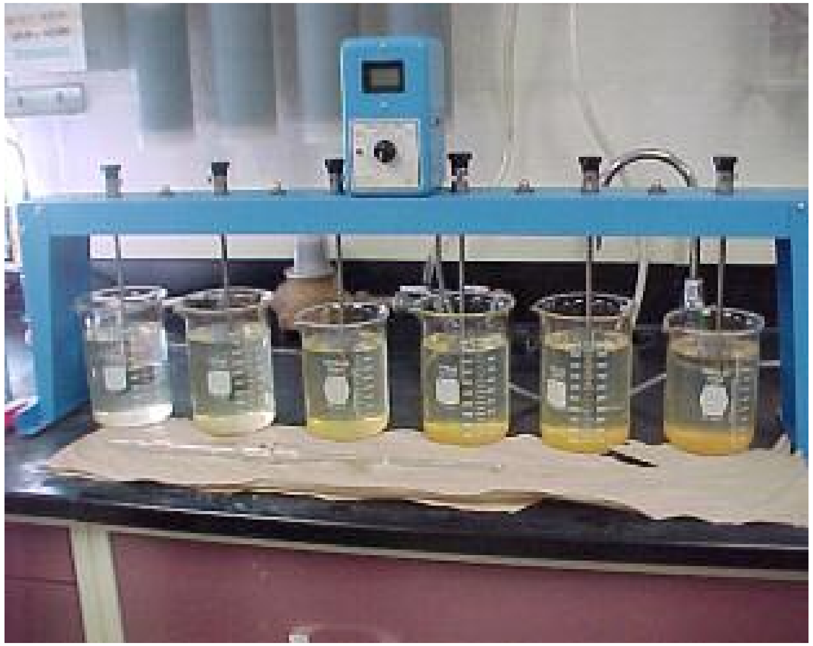
- Adjust pH of the jars while mixing using H_2SO_4 or NaOH/lime (pH: 5.0; 5.5; 6.0; 6.5; 7.0; 7.5)

- Add same dose of the selected coagulant (alum or iron) to each jar (Coagulant dose: 5 or 10 mg/L)

Jar Tests – determining optimum pH

- Rapid mix each jar at 100 to 150 rpm for 1 minute. The rapid mix helps to disperse the coagulant throughout each container

- Reduce the stirring speed to 25 to 30 rpm and continue mixing for 15 to 20 mins
This slower mixing speed helps promote floc formation by enhancing particle collisions, which lead to larger flocs



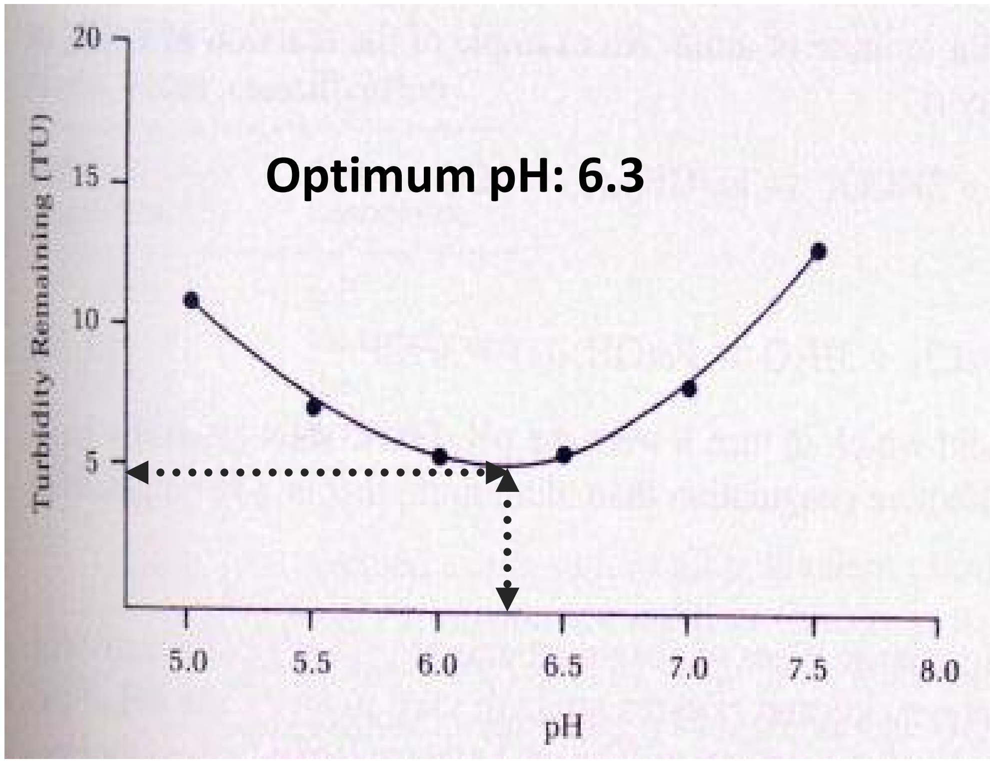
- Turn off the mixers and allow flocs to settle for 30 to 45 mins

- Measure the final residual turbidity in each jar

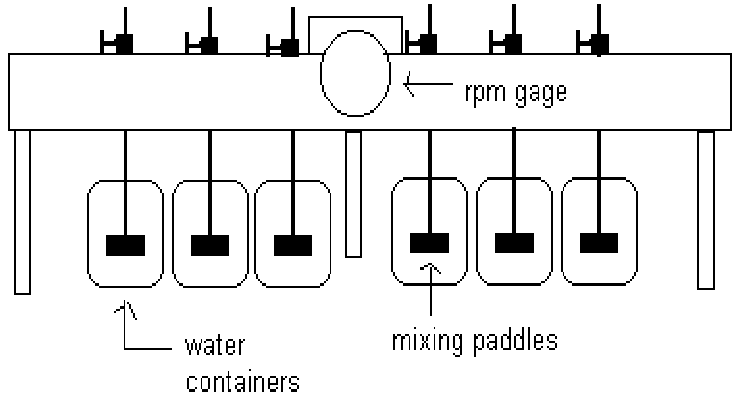
- Plot residual turbidity against pH

Jar Tests – optimum pH

- The pH with the lowest residual turbidity will be the optimum pH



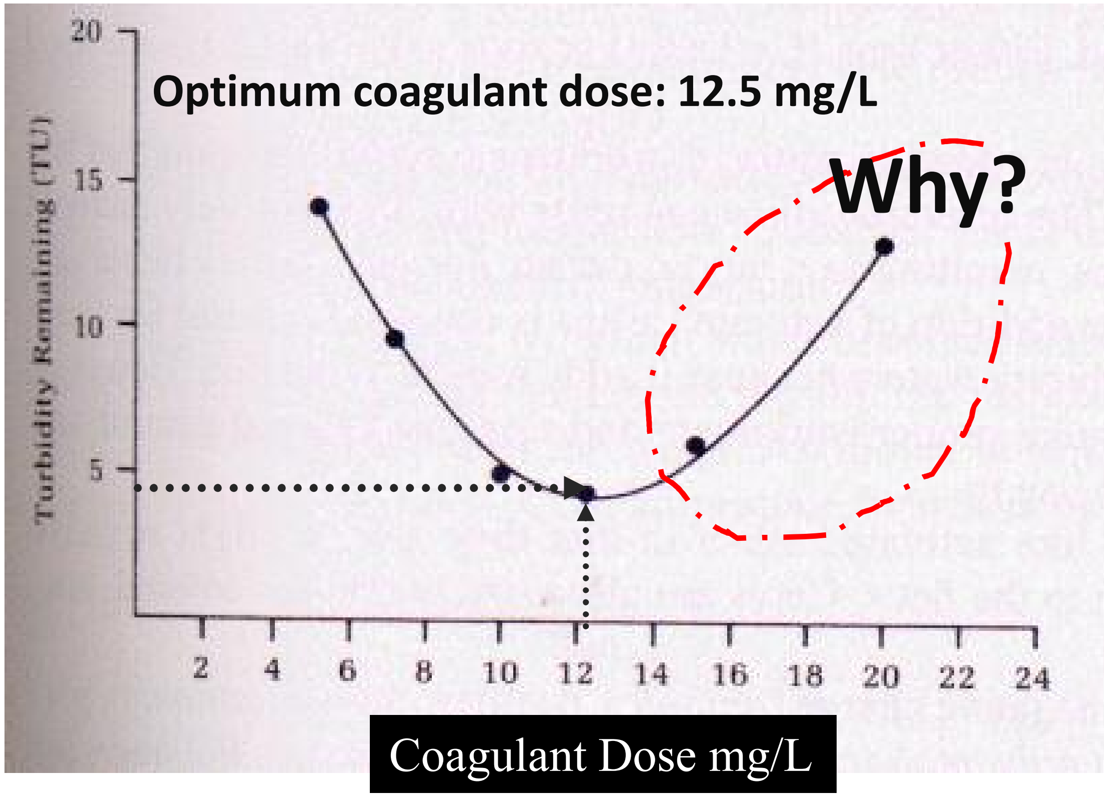
Jar Test: Optimum coagulant dose



- Repeat all the previous steps
- This time adjust pH of all jars at optimum (6.3 found from first test) while mixing using H_2SO_4 or NaOH/lime
- 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. The rapid mix helps to disperse the coagulant throughout each container
- Reduce the stirring speed to 25 to 30 rpm for 15 to 20 mins

Optimum coagulant dose

- ❑ Turn off the mixers and allow flocs to settle for 30 to 45 mins
- ❑ Then measure the final residual turbidity in each jar
- ❑ Plot residual turbidity against coagulant dose



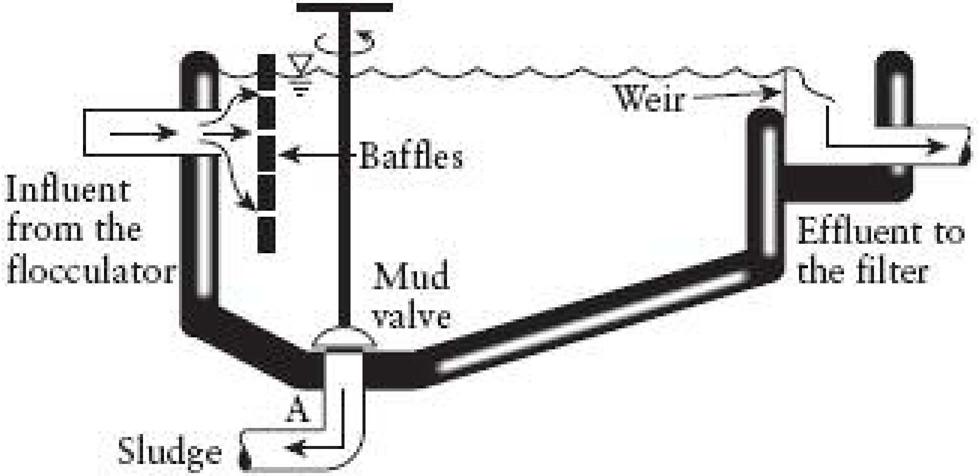
➢ The coagulant dose with the lowest residual turbidity will be the optimum coagulant dose

Sedimentation

- Separation of formed flocs from water in *gravity settling tanks* that simply allow the heavier-than-water particles to settle to the bottom.

➢ Settling depends on:

  - particle size (volume)
  - particle shape
  - particle density
  - fluid density
  - fluid viscosity.



Particle Diameter (mm)	Typical Particle	Settling Velocity (m/s)
1.0	Sand	2×10^{-1}
0.1	Fine sand	1×10^{-2}
0.01	Silt	1×10^{-4}
0.001	Clay	1×10^{-6}

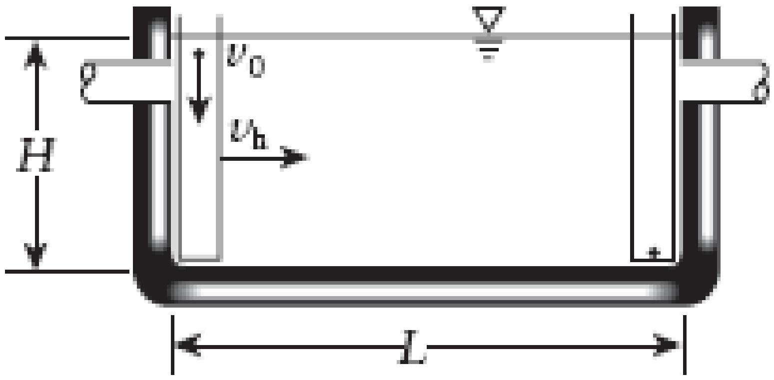
Ideal settling tank

- visualized hydraulically as perfect plug flow reactors

Overflow rate:

$$v_0 = \frac{\text{m}}{\text{s}} = \frac{Q}{A_s} = \frac{\text{m}^3/\text{s}}{\text{m}^2}$$

$$v_0 = \frac{H}{\bar{t}}$$



Examples: *10.16 10.17 10.18*

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

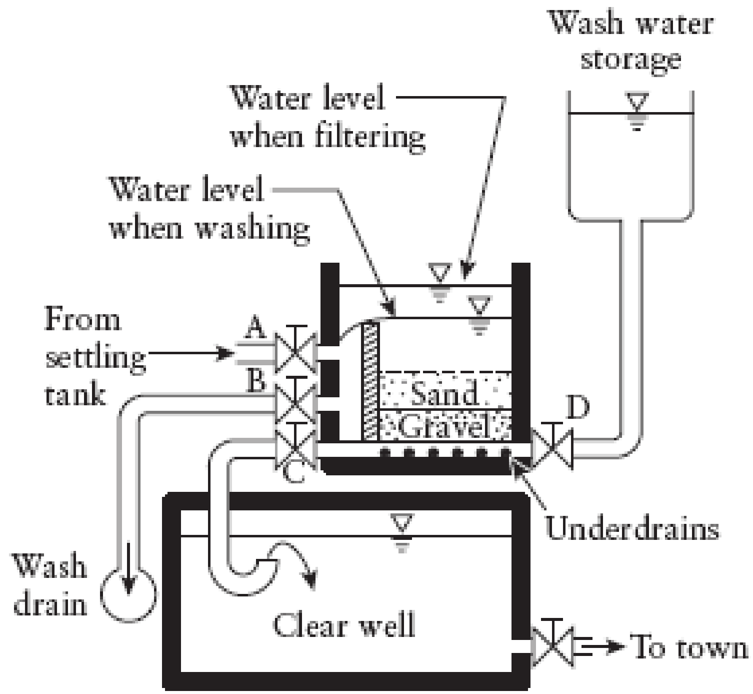
- Slow sand filters
- Rapid sand filters

Rapid sand filter

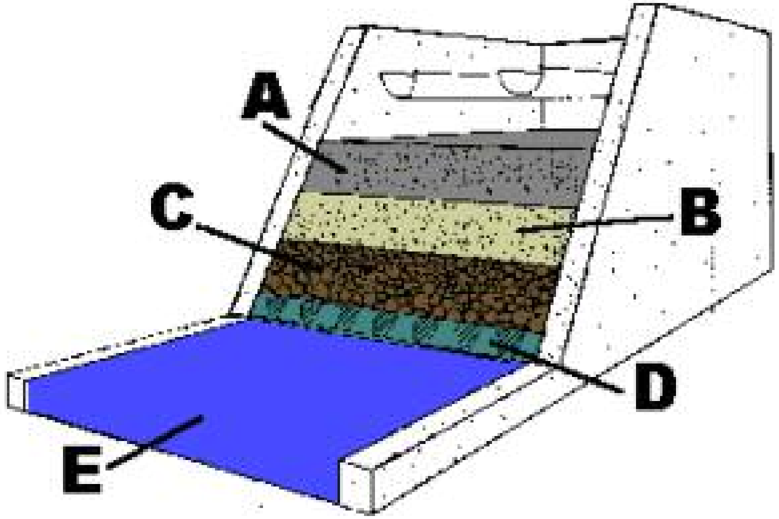
- The operation of a rapid sand filter involves two phases: filtration and washing.

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

✓ rapid sand filter becomes clogged, resulting greater head loss through the filter, so it must be cleaned. This cleaning is performed hydraulically by a process called backwashing (10 - 15min).



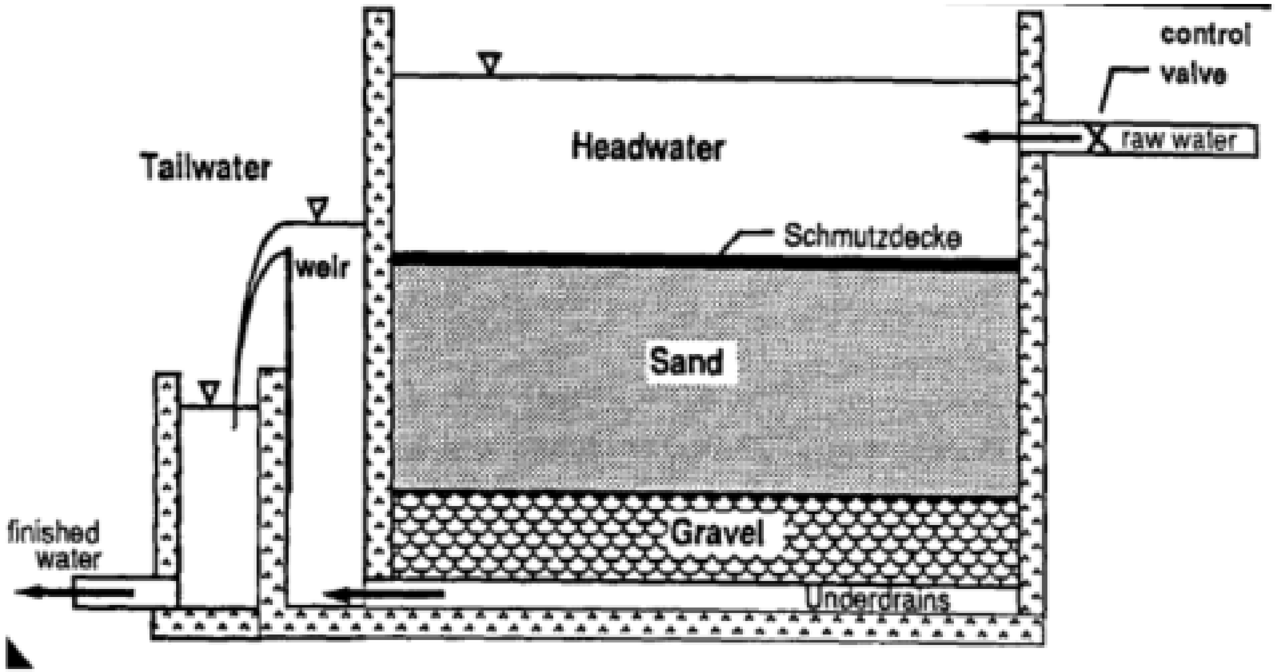
Rapid Filter Media



- Single media: sand
- Dual media: anthracite coal and sand
- Multimedia: anthracite coal, sand and garnet

Slow sand filter

- **Slow-sand filters:** (dp=0.15-0.35mm) require a much larger area. The top 1 inch must be periodically scraped off and the filter occasionally back-washed

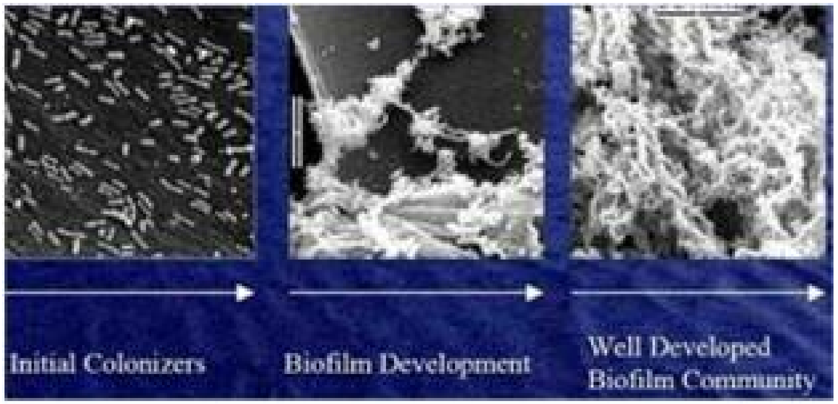


Biological Layer: The Schmutzdecke

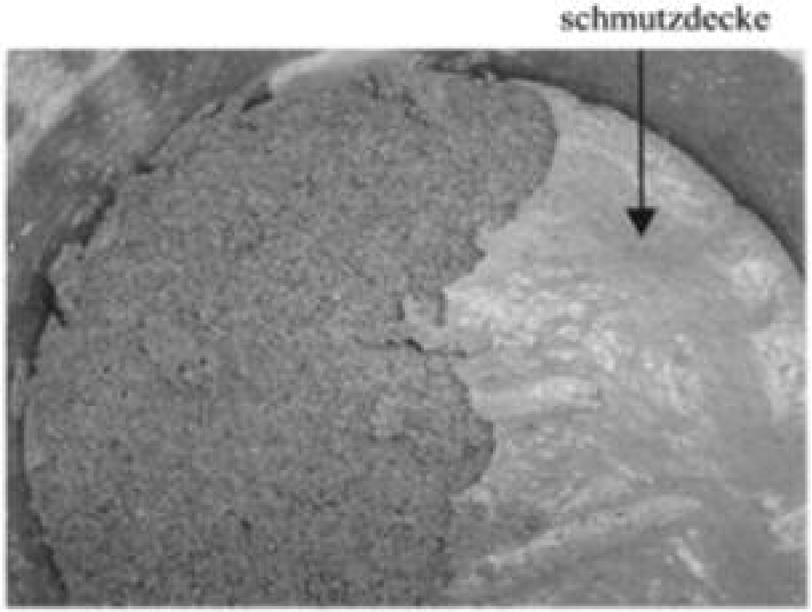
- Due to the organic and biological matter in the water to be filtered, a bio-layer grows on top of the sand layer

- The bio-layer contributes to water treatment by consuming organic contaminants including bacteria and viruses

- The majority of biological activity occurs in the top 20 cm of the filter



Biofilm Development



Layer of Schmutzdecke

Disinfection

- water completely free of suspended sediment is treated with a powerful oxidizing agent usually chlorine, chlorine then ammonia (chloramine), or ozone.

  - ✓ Disinfection is typically the last step in a water / wastewater treatment system
  - ✓ A residual 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.

Disinfectants

- **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

- **Chlorine dioxide (ClO_2):**
  - No disinfection by-products such as trihalomethanes

- **$Ca(ClO)_2$:**
  - Safer than Cl_2

- **Ozone**: generated on site

- **UV lamps**

Chemistry of Chlorine in Water

HOCl = Hypochlorous acid
OCl^- = Hypochloride ion

- $Cl_2 + H_2O \rightarrow H^+ + Cl^- + HOCl$
  - HOCl is a weak acid with Ka = 4.5×10^{-4} ($HOCl == H^+ + OCl^-$)
  - HOCl and OCl^- are <u>free available chlorine</u> which are very effective in killing bacteria
- Small amount of ammonium (NH_4^+) in water is desired
  - Chloramines: NH_2Cl, $NHCl_2$, NCl_3
  - Chloramines (<u>combined available chlorine</u>) are weaker disinfectants than free available chlorine but are desired residual chlorine to be retained in water distribution system
- Excessive amount of ammonium (NH_4^+) in water is undesirable because it consume excess demand of Cl_2

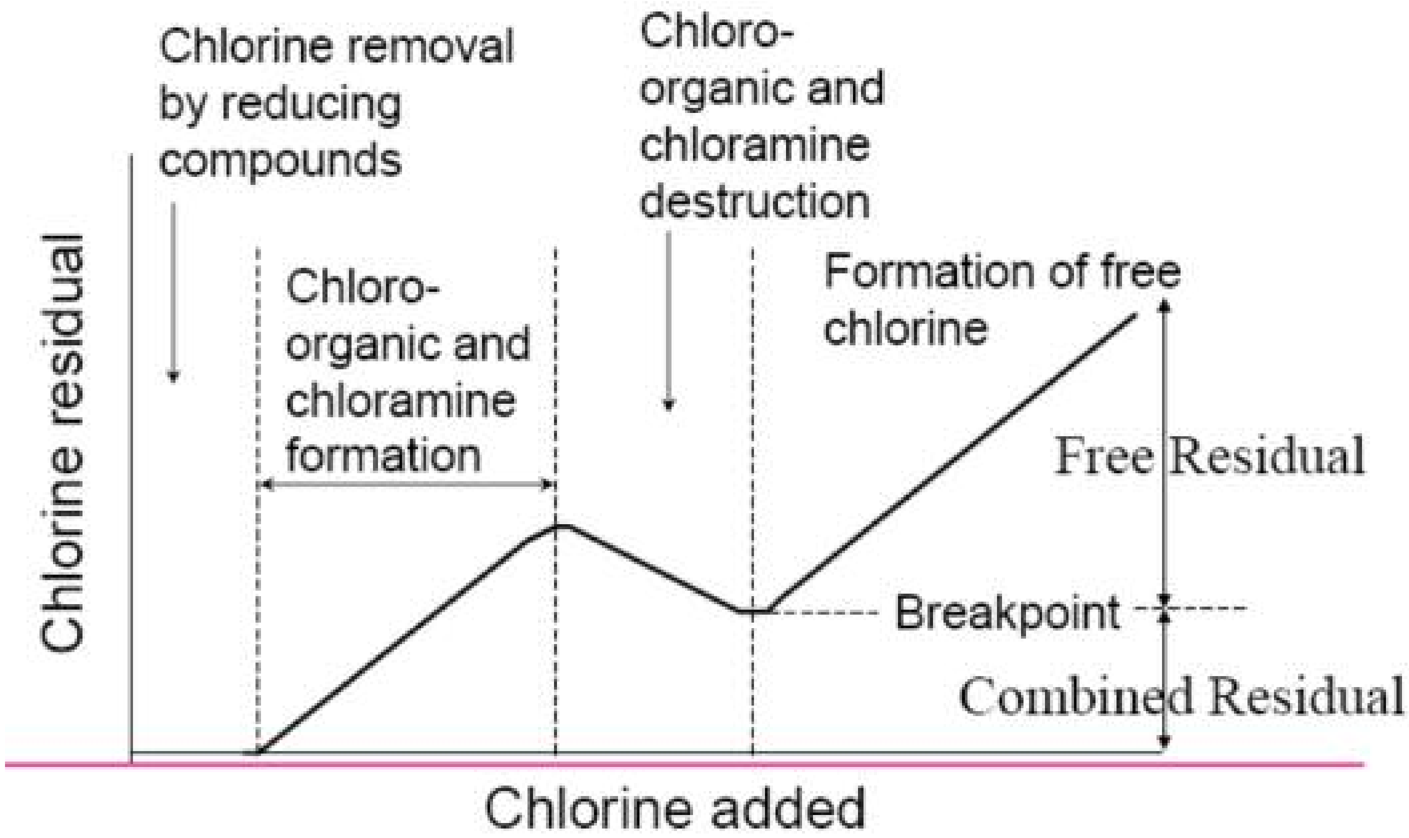
Disinfectant	Minimum Residual* (mg/L)		MRDL** (mg/L)	MRDLG*** (mg/L)
	Leaving Plant	In Distribution System		
Chloramines (as Cl_2)	2.0		4.0	4.0
Combined residual		0.5		
Chlorine (as Cl_2)	2.0		4.0	4.0
Chlorine dioxide (as ClO_2)	2.0		0.8	0.8
Free chlorine residual		0.2		

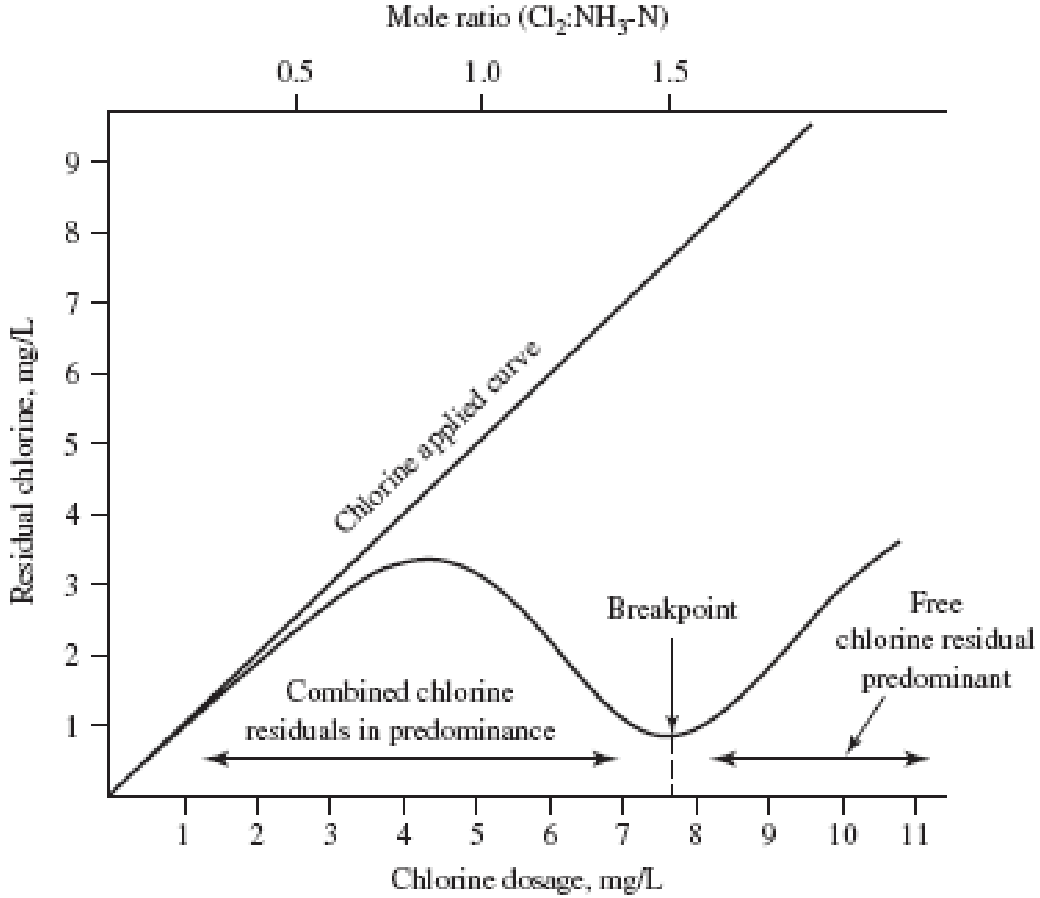
* From Illinois and Missouri regulations.

** MRDL = maximum residual disinfectant level.

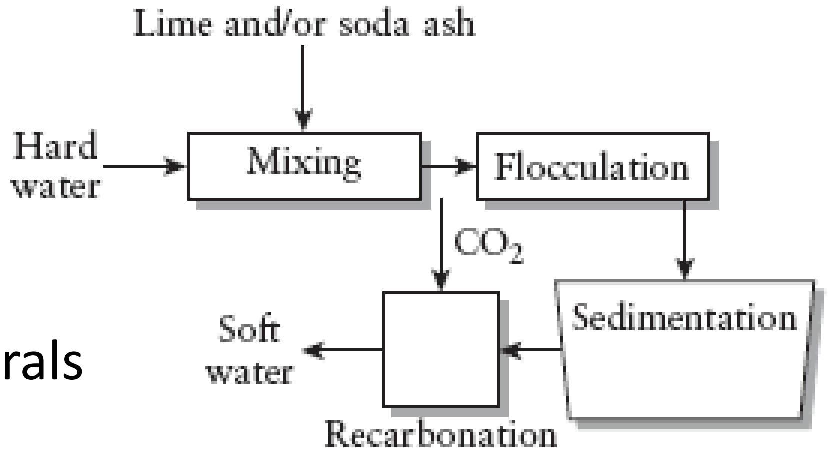
** MRDLG = maximum residual disinfectant level goal.

Chlorine Demand or Breakpoint Chlorination




Mole ratio (Cl_2:NH_3-N)
0.5
1.0
1.5
9
8
7
6
5
4
3
2
1
Residual chlorine, mg/L
Chlorine applied curve
Breakpoint
Free
chlorine residual
predominant
Combined chlorine
residuals in predominance
1
2
3
4
5
6
7
8
9
10
11
Chlorine dosage, mg/L

Groundwater Treatment

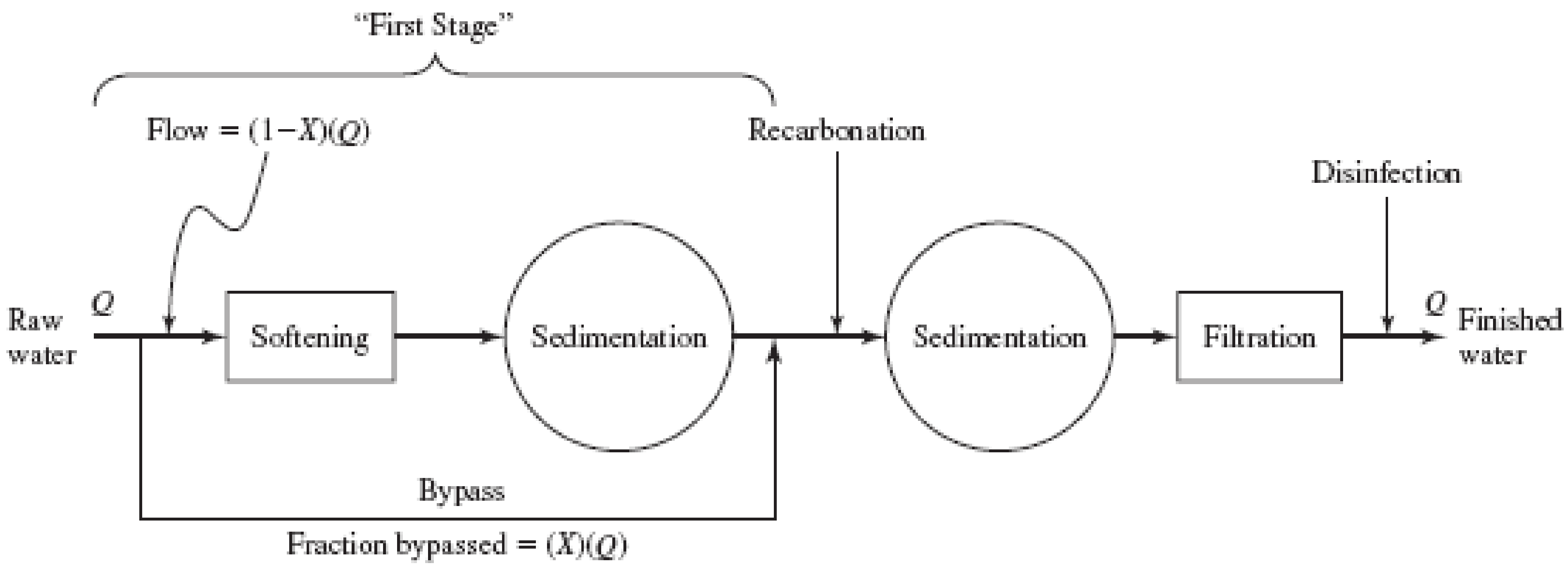


- **Primary objectives are to**

  1. Remove hardness and other minerals

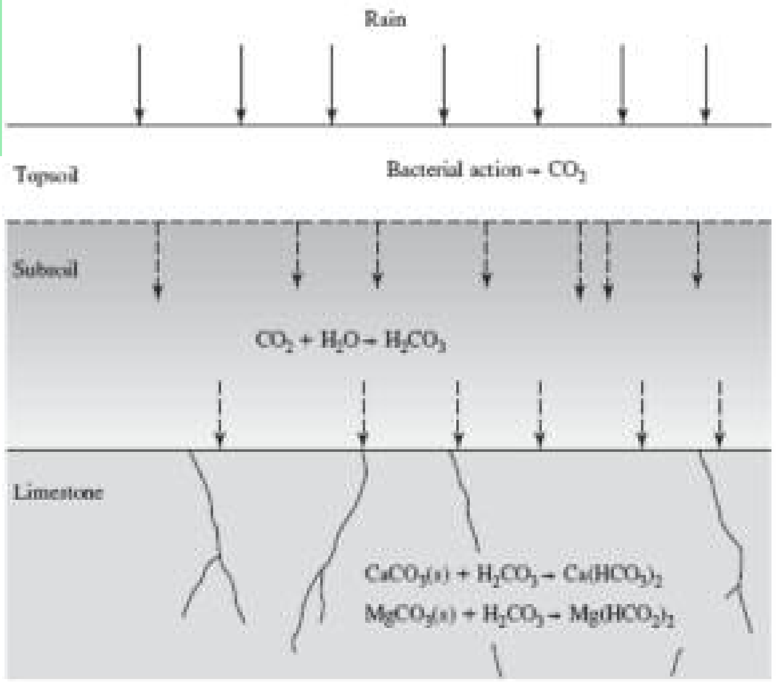
  2. Eliminate pathogenic organisms

- Treatment technologies largely based on chemical precipitation


"First Stage"
Flow = (1−X)(Q)
Recarbonation
Disinfection
Raw water
Q
Softening
Sedimentation
Sedimentation
Filtration
Q
Finished water
Bypass
Fraction bypassed = (X)(Q)

Water Softening

- Groundwater is generally harder than surface water.
- Hard waters produce scale in hot-water pipers, heaters and boilers.
- The removal of ions that cause hardness is called softening.



- Softening can be accomplished by the lime-soda process, ion exchange, nanofiltration, or reverse osmosis.
- Principal cations causing hardness and the major anions associated with them (in decreasing order of abundance in natural waters)

➢ Cations: Ca2+, Mg2+, Sr2+, Fe2+, Mn2+

➢ Anions: HCO3-, $SO_4$2-, Cl-, NO_3-, $SiO_3$2-

Water Softening Methods

1. LIME-SODA SOFTENING

- ***Quicklime*** (CaO), commonly called ***lime**, and* hydrated lime [$Ca(OH)_2$]:

- *Slaking:* $CaO + H_2O \rightleftharpoons Ca(OH)_2 + \text{heat}$

Softening Methods;

- **lime-only process:** when Ca^{2+} is present primarily as "bicarbonate hardness"

- **lime-soda [$Ca(OH)_2$-Na_2CO_3] process:** when bicarbonate is not present at substantial level

RXNs

Neutralization of carbonic acid

$$CO_2 + \mathbf{Ca(OH)_2} \rightleftharpoons CaCO_3(s) + H_2O$$

Precipitation of carbonate hardness

$$Ca^{2+} + 2HCO_3^- + \mathbf{Ca(OH)_2} \rightleftharpoons 2CaCO_3(s) + 2H_2O$$

$$Mg^{2+} + 2HCO_3^- + \mathbf{Ca(OH)_2} \rightleftharpoons MgCO_3 + CaCO_3(s) + 2H_2O$$

$$MgCO_3 + \mathbf{Ca(OH)_2} \rightleftharpoons Mg(OH)_2(s) + CaCO_3(s)$$

Precipitation of noncarbonate hardness due to calcium

$$Ca^{2+} + \mathbf{Na_2CO_3} \rightleftharpoons CaCO_3(s) + 2Na^+$$

Precipitation of noncarbonate hardness due to magnesium

$$Mg^{2+} + \mathbf{Ca(OH)_2} \rightleftharpoons Mg(OH)_2(s) + Ca^{2+}$$

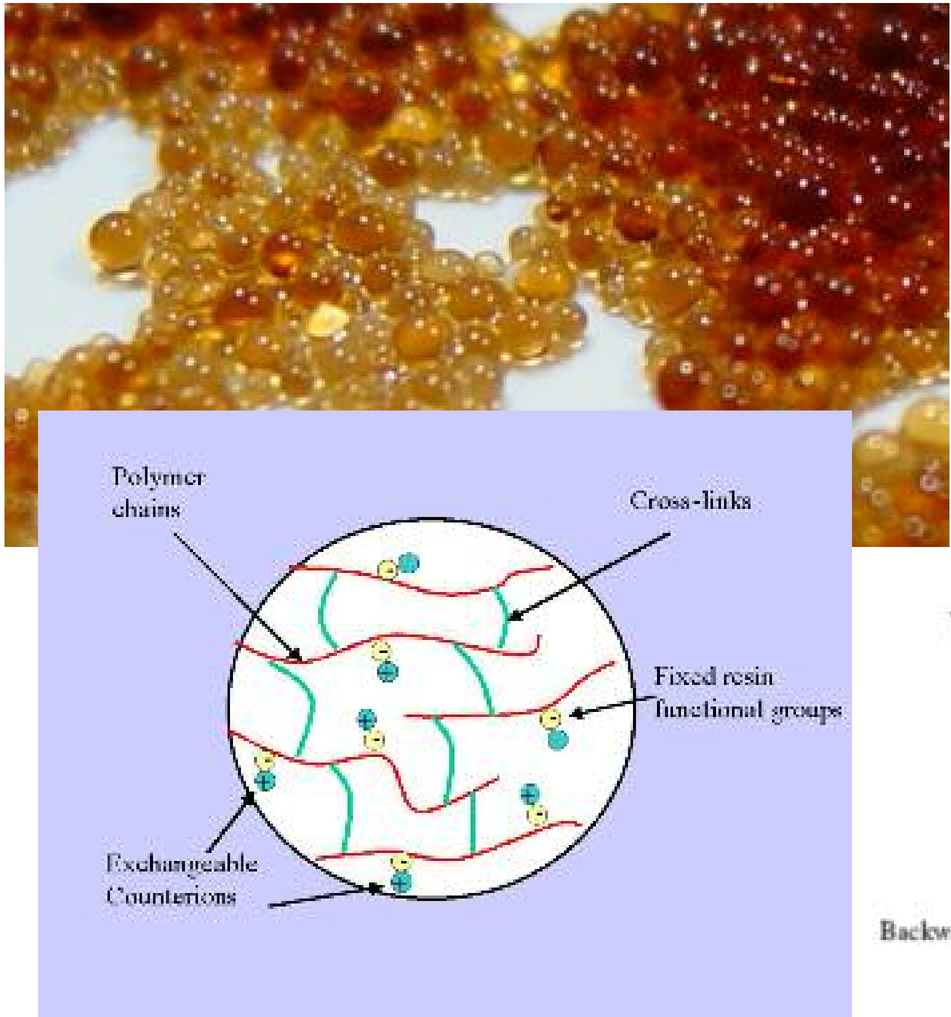
$$Ca^{2+} + \mathbf{Na_2CO_3} \rightleftharpoons CaCO_3(s) + 2Na^+$$

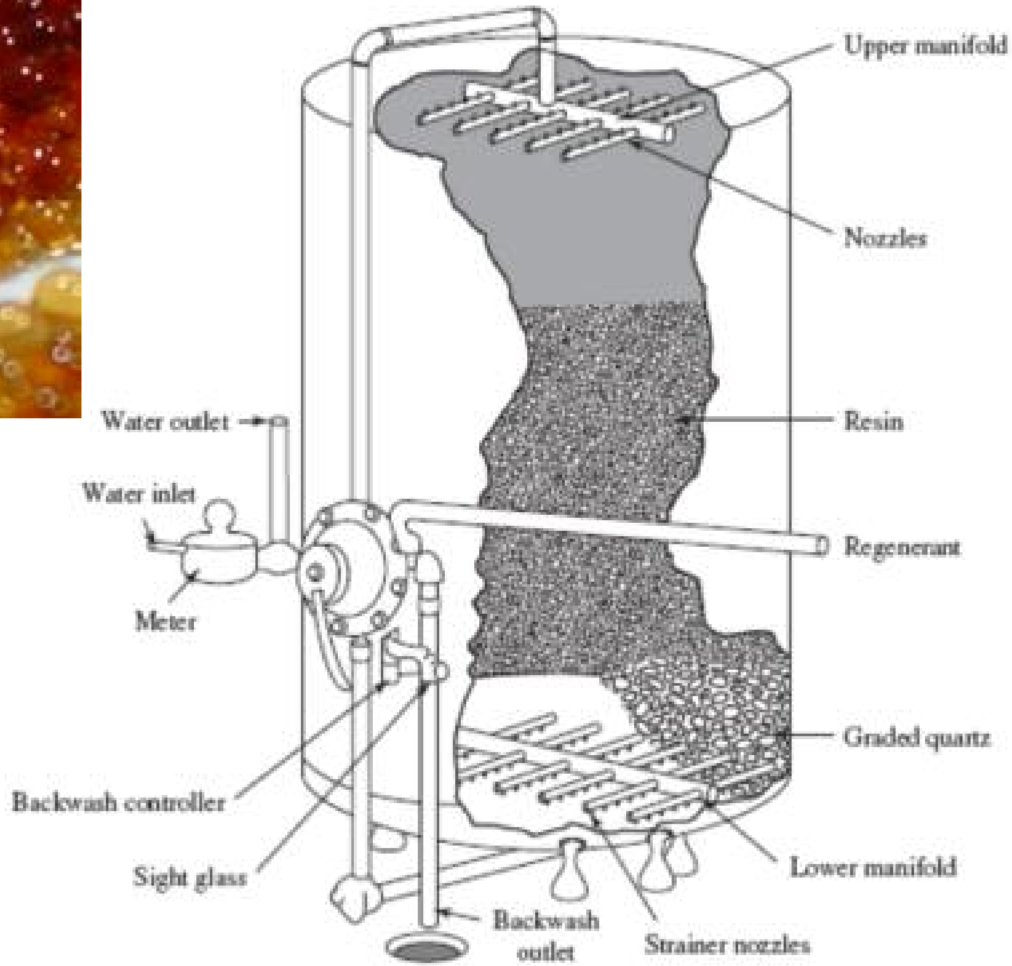
Summary of chemical additions to soften water

Step	Chemical addition[a]	Reason
Carbonate hardness		
1.	Lime = CO_2	Neutralize 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-}

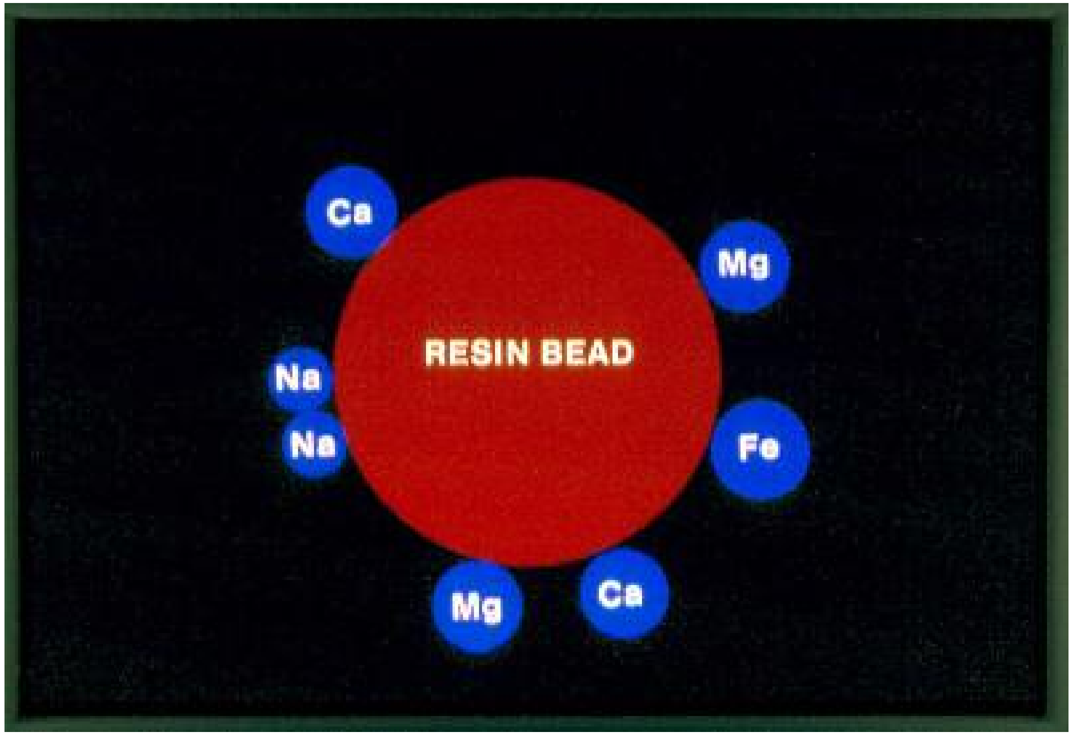
[a]The terms "Lime" and "Soda"refer to mg/L of $Ca(OH)_2$ and Na_2CO_3 respectively, as $CaCO_3$ equal to mg/L of ion (or gas in the case of CO_2) as $CaCO_3$.

Ion Exchange

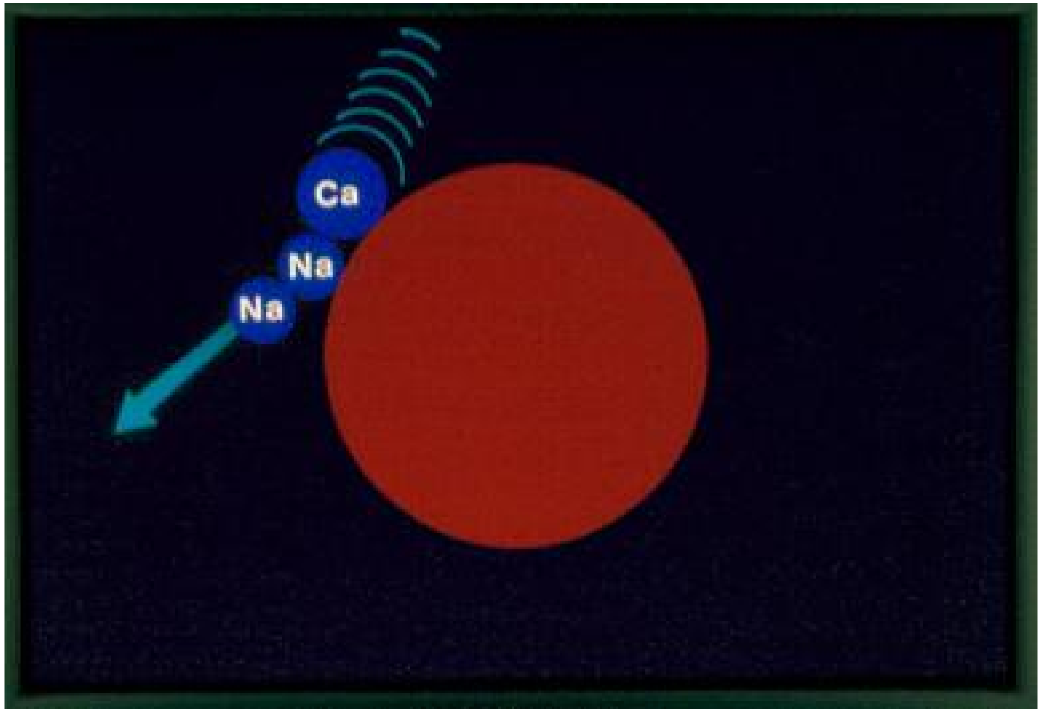




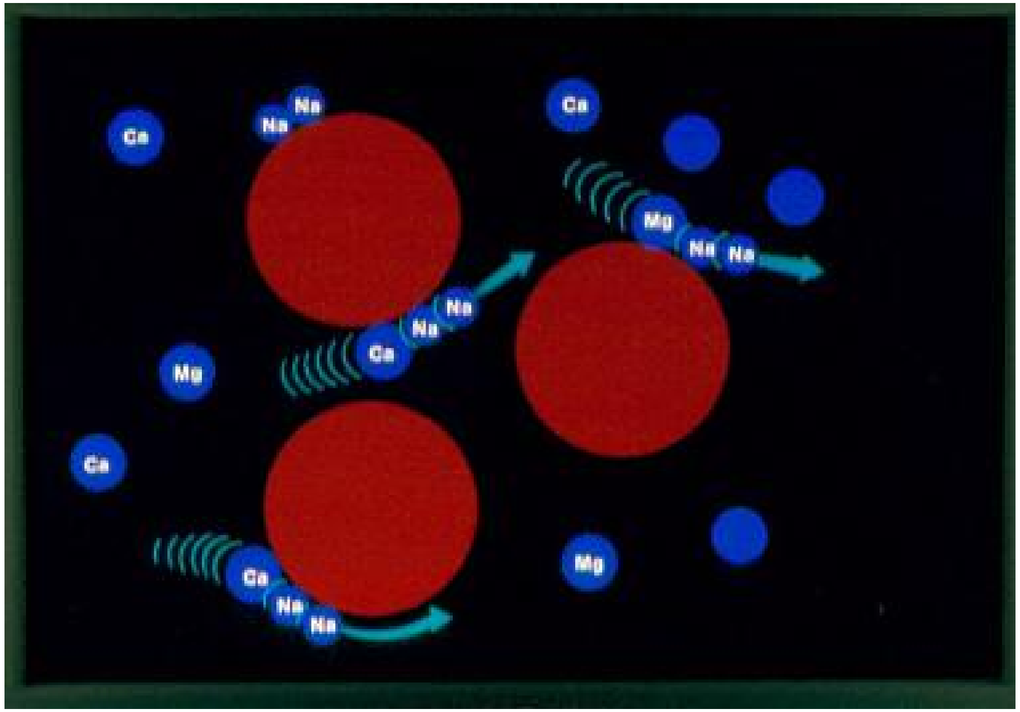
Resin



- Cation resin bead attract and hold positively charged ions.
- Those ions remain on the bead until the bead encounters other ions for which it has a greater affinity.

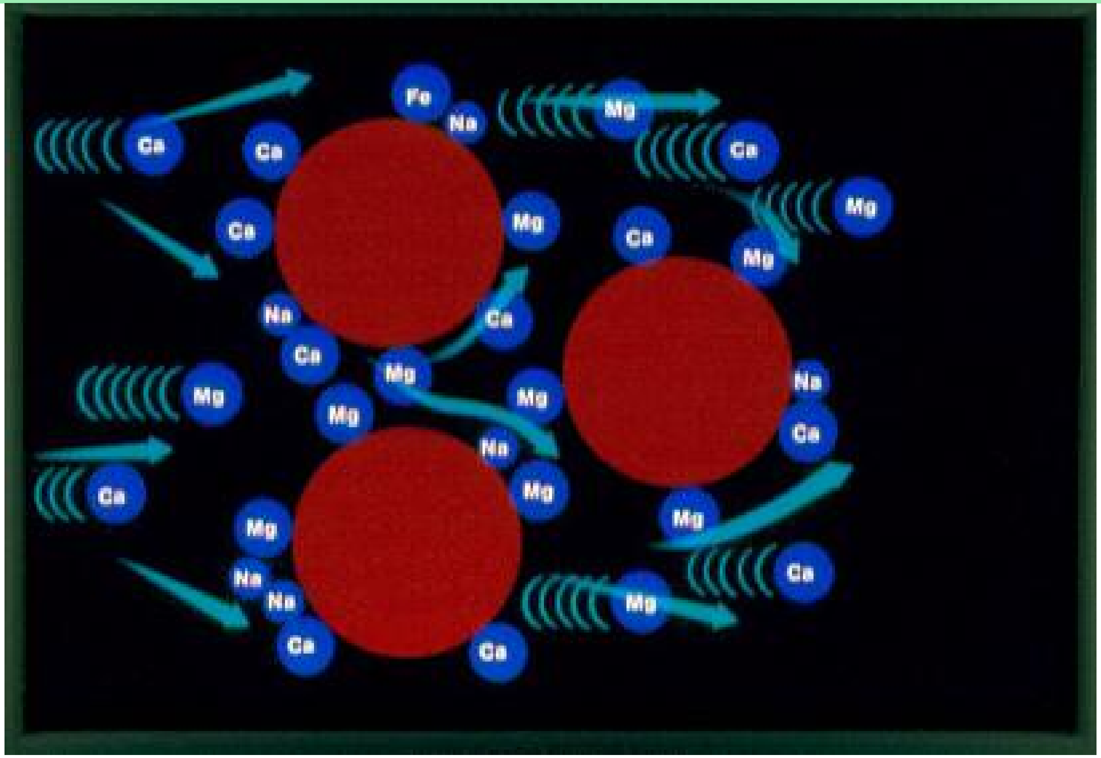


- Resin bead releases Na^+ and absorbs Ca^{+2} and Mg^{+2} ions for which it has a greater attraction.
- Ions are not destroyed or changed chemically; they are simply replaced on the resin bead.
- This process is known as ion exchange.



- Resin beads attract Ca^{+2} and Mg^{+2} ions and release Na^{+}

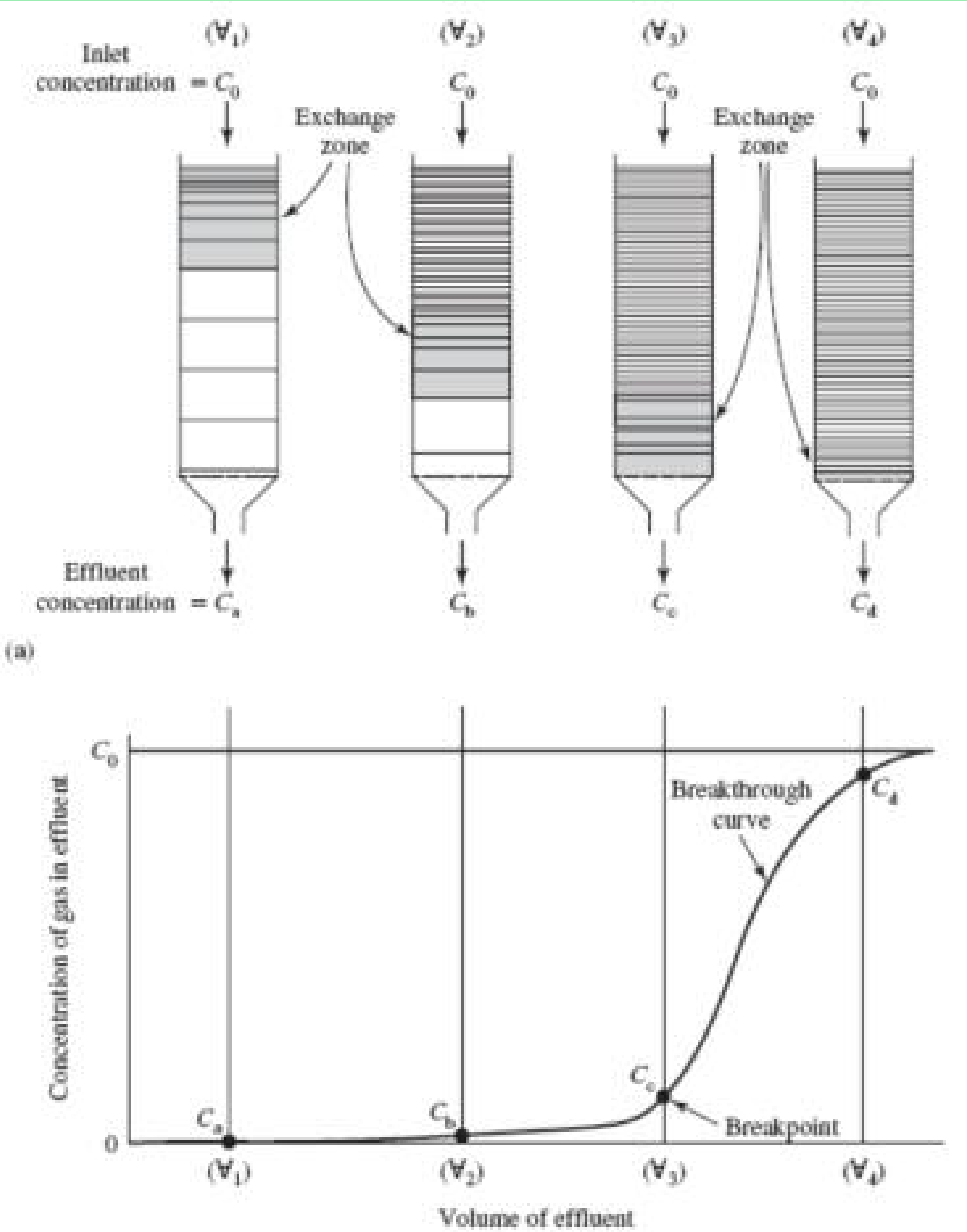
- Water has been softened because the Ca^{+2} and Mg^{+2} concentrations, which cause water hardness have been reduced.



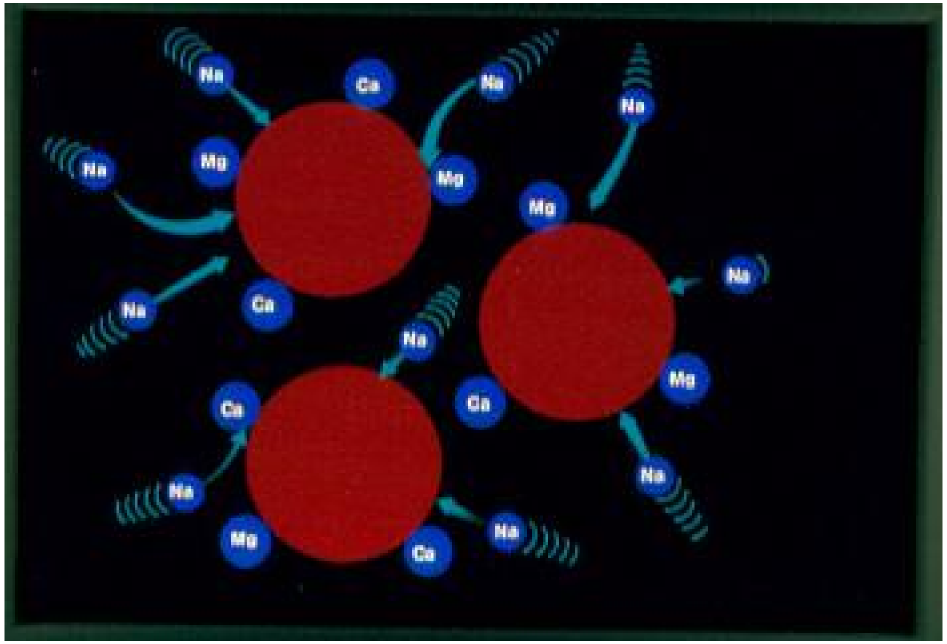
- After a vast number of Ca^{+2} and Mg^{+2} ions have become attached to the resin beads, and most of the Na^{+} ions have been released, the resin can no longer soften the water.
- If no new chemical reaction is set, the incoming Ca^{+2} and Mg^{+2} ions flow untouched through the unit because there is no room for them on the resin beads.

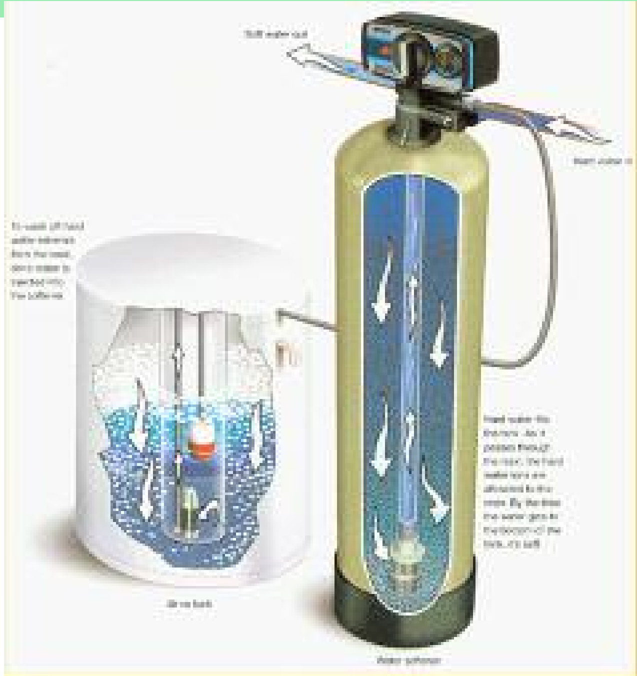
Breakthrough Curve

- It is more typical at municipal plants for the breakthrough criterion to be set much lower, for example, at 5% to 10% of the influent concentration.



Resin Regeneration





- The reaction can be reversed by greatly increasing the concentration of sodium in the solution.

- Reverse process drive the Ca^{+2} and Mg^{+2} ions off the resin beads and replace them with Na^{+} ions.

- Although the resin beads prefer Ca+2 and Mg+2 ions, the excessive concentration of Na+ ions overcomes this affinity.

Recarbonation

- When the pH of the softened water is greater than the saturation pH, the pH must be reduced to stop the precipitation reaction that will deposit $CaCO_3$ in the filters and distribution system piping because this will cement them closed.

- CO_2 (which when dissolved in water forms H_2CO_3) has frequently been found to be the most economical chemical to use in reducing the pH.

- Alternatively, strong acids such as sulfuric acid may be employed.

HW

10.8

10.9

10.12

10.16

10.17