

# 5. Coagulation, Softening, Flocculation, Sedimentation and Filtration

## Objective

In this lesson we will answer the following questions:

- How do coagulation and flocculation fit into the water treatment process?
- Which chemicals are used in coagulation?
- What factors influence coagulation and flocculation?

- **Coagulation** consist of adding a floc forming chemical reagent to a water to combine with nonsettleable colloidal solids so they can stick together.
- Colloids are negatively charged particles. The addition of a coagulant, which has positively charged particles, would neutralize the negative charge on the colloids.
- Slow settling suspended solids to produce a rapid settling floc. The floc is subsequently removed in most cases by **sedimentation**.
- **Flocculation** is the slow stirring or gentle agitation to aggregate the destabilized particles and form a rapid settling floc.
- Mixing of the coagulated suspension to promote colloid-contact forming larger solids called flocs that can be removed by gravity settling

Particles	Size (mm)	Settling Velocity
Coarse sand	1	0.23 m/s
Fine sand	0.1	0.6 m/min
Silt	0.01	8.6 m/day
Large colloid	0.0001	0.3 m/year
Fine colloid	0.000001	3 m/mil. year

# Colloidal Particles

- particulates in water source that contribute to colour and turbidity
- mainly clays, silts, viruses, bacteria, fulvic and humic acids and organic particulates
- at pH levels above 4.0, particles or molecules are generally negatively charged
- have a very large ratio of surface area to volume



## Uses of Coagulation

The primary purpose of the coagulation process is the removal of turbidity from the water. **Turbidity** is a cloudy appearance of water caused by small particles suspended therein. Water with little or no turbidity will be clear.

## Methods of Coagulation Process

- mixing water with coagulant chemicals such as alum or ferric chloride
- the purpose of rapid mixing is to provide a uniform dispersion of coagulant chemical throughout the influent water
- coagulant chemicals can be mixed by several methods, including:
  - Mechanical method: *flume mixer*
  - Hydraulic method: *flash mixer*

## Factors Affected Coagulation Process

- Coagulant dosage
- Adjustment of pH
- Turbidity

# Types of Mixture

- Mechanical mixer (Propellers or paddle types mixer)
- In-line mixers
- Pump mixers

## Important Parameter in Rapid and slow mixing

- Mixing time
- $t \approx 30$  seconds for coagulation
- $t \approx 20 - 40$  minutes for flocculation
- Velocity Gradient (G)
- $G$ , reflects the degree of mixing

$$G = \left[ \frac{P}{V\mu} \right]^{0.5}$$

$G$  = velocity gradient (second-1 or  $s^{-1}$ )

$P$  = Power input (W or N.m/s)

$V$  = Volume of mixing tank ( $m^3$ )

$\mu$  = dynamic viscosity of water ( $N.s/m^2$ ) =  $1.0 \times 10^{-3} N.s/m^2$  at  $20^\circ C$

$G = 10 - 70 s^{-1}$ ,  $GT = 10,000 - 100,000$  for flocculation

Large  $G$  values produce small, dense flocs.

Small  $G$  values produce larger, lighter flocs.

# Factors Affecting Coagulation/Flocculation

1. The most commonly used coagulants are:

- Alum (aluminium sulphate),  $\text{Al}_2(\text{SO}_4)_3 \cdot 14.3 \text{ H}_2\text{O}$
- Ferric chloride,  $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ ,
- Ferric sulphate,  $\text{Fe}_2(\text{SO}_4)_3$ ,
- Cationic polymers.

2. Coagulant concentration (1% - 3%)

3. pH

**Alum:** 5.5 – 7.5 (Optimum pH  $\approx$  7.0)

**Ferric:** 5.5 – 8.5 (Optimum pH  $\approx$  7.5)

4. Chemical composition of water (eg.  $\text{SO}_4^{=}$ ,  $\text{CO}_3^{=}$ ,  $\text{PO}_4^{=}$ )

## 5. Nature of Turbidity

Particles of different size are easier to coagulate than uniform size particle.

Highly turbid waters may require a lesser amount of coagulant than waters with slight turbid.

## 6. Temperature

Cold water near 0 °c is difficult to coagulate

## 7. Rapid mixing (degree and type of mixing)

## 8. Coagulant / flocculant aids

Aids are used to improve settling and strength of flocs and to enhance turbidity and colour removal.

Examples of aids: activated silica, oxidants (chlorine, ozone, potassium permanganates to aid in color removal), and polymers.

# Theoretical Chemical Reaction

- Aluminium Sulphate (Alum)
- Alum reacts with natural alkalinity forming hydroxide flocs,  $Al(OH)_3$ .



MW: 600                       $3 \times 100 = 300$   $CaCO_3$                $2 \times 78$

EW:  $600/6 = 100$                        $100/2 = 50$                $78/3 = 26$

600 parts of alum use up 300 parts of alkalinity as  $CaCO_3$

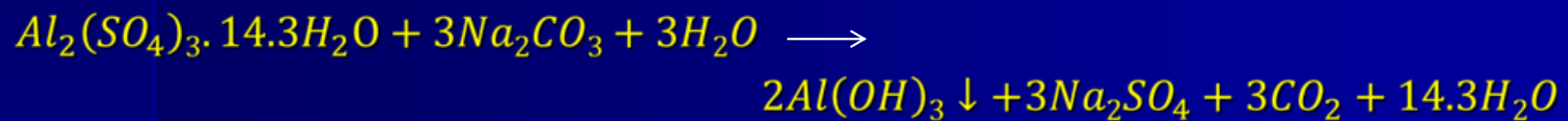
i.e. Each mg/L of alum decreases water alkalinity by 0.5 mg/L as  $CaCO_3$

Therefore, the overall effect of alum addition will be a decrease in pH of water because  $CO_2$  is formed from the reaction.



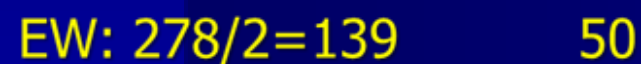
Note: ■

If water does not contain sufficient alkalinity to react with alum, lime  $\text{Ca(OH)}_2$  or soda ash  $\text{Na}_2\text{CO}_3$  is added to provide the necessary alkalinity:



## Ferrous Sulfate (Copperas)

■ Ferrous sulfate reacts with natural alkalinity:



278 parts of ferrous sulfate react or use 100 parts of alkalinity as  $\text{CaCO}_3$  i.e. 1 mg/L of ferrous sulfate uses 0.36 mg/L of alkalinity as  $\text{CaCO}_3$

## Note:■

- Lime  $\text{Ca(OH)}_2$  has to be added to raise the pH to the point where ferrous ions are precipitated as ferric hydroxide ( $\text{pH} \approx 9.0$ ). If ferrous ion are not completely removed, they add color to water.
- This process may be cheaper than alum coagulation but the dosing operation with two chemicals is more difficult.

## Ferric Sulfate

- Ferric sulfate reacts with natural alkalinity:



$$\text{MW: } 400 \quad 3 \times 100 \quad \rightarrow$$

$$\text{EW: } 400/6 \quad 50$$

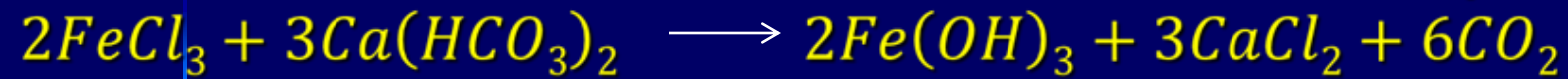
1 mg/L of ferric sulfate uses 0.75 mg/L of alkalinity as  $\text{CaCO}_3$ .

## Note:

- Ferric sulfate is used for color removal at low pH
- At low pH (lime addition), ferric sulfate may be used for iron and manganese removal and it may be used as a coagulant in precipitation softening.

## ■ Ferric Chloride

### ■ Ferric chloride reacts with natural alkalinity:



MW: 162                  300

EW: 27                  50

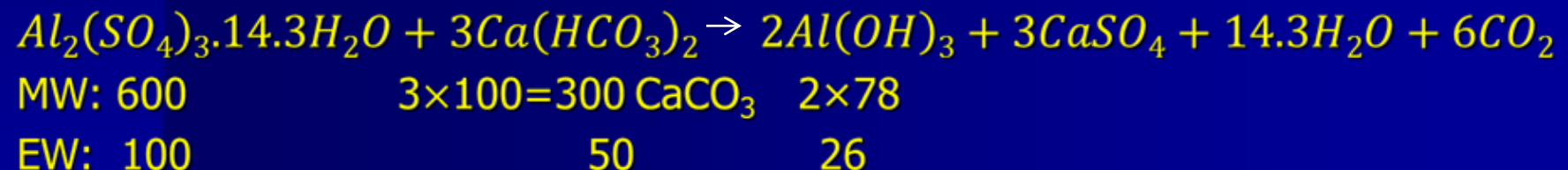
1 mg/L of ferric chloride uses 1.8 mg/L of alkalinity as  $CaCO_3$

# Example

A dose of 36 mg/L of alum is used in coagulation turbid water with turbidity = 10 NTU

- (a) How much alkalinity is consumed?
- (b) What changes take place in the ionic character of the water?
- (c) How much mg/L of  $Al(OH)_3$  are produced?
- (d) What is the amount of sludge produced (mg/L or g/m<sup>3</sup> of water)?
- (e) What is the volume of sludge produced (m<sup>3</sup>/m<sup>3</sup> of water) if the solids concentration in sludge = 0.2% (i.e. 2000 mg/L)?

## Solution



- (a) 1 mg/L of alum consumes 0.5 of water alkalinity as  $CaCO_3$   
 $\therefore$  Alkalinity consumed =  $0.5 \times 36 = 18$  mg/L as  $CaCO_3$

(b)  $\text{SO}_4^{2-}$  is added, and  $\text{HCO}_3^-$  is consumed and converted to  $\text{CO}_2$

$$\text{EW of } \text{SO}_4^{2-} = 48 \quad \text{EW of } \text{HCO}_3^- = 61$$

$$\therefore \text{amount of } \text{SO}_4^{2-} \text{ added} = (48/100) \times 36 = 17.3 \text{ mg/L}$$

$$\& \text{ amount of } \text{HCO}_3^- \text{ consumed} = (61/50) \times 18 = 22 \text{ mg/L}$$

Note: Calcium content is not affected.

$$(c) \text{ Al(OH)}_3 \text{ produced} = (26/100) \times 36 = 9.6 \text{ mg/L}$$

$$(d) \text{ Sludge produced} \approx 9.4 + \text{turbidity} = 9.4 + 10 = 19.4 \text{ mg/L} \\ = 19.4 \text{ g/m}^3 \text{ of water}$$

$$(e) \text{ Solids concentration} = 0.2\% = 2000 \text{ mg/L} = 2000 \text{ of} \\ \text{solids/m}^3 \text{ of sludge}$$

$$\text{Volume of sludge} = \frac{19.4 \text{ g solids / m}^3 \text{ water}}{2000 \text{ g solids / m}^3 \text{ sludge}} \\ = 0.0097 \text{ m}^3 \text{ sludge / m}^3 \text{ sludge}$$



## Example

Treatment of 35,000 m<sup>3</sup>/day of water requires 20 mg/L of alum as a coagulant. The natural alkalinity of the water is equivalent to 4 mg/L of CaCO<sub>3</sub>.

- (a) What dosage of lime as CaO needs to be added in order to react with alum after the natural alkalinity is exhausted?
- (b) Determine the required quantities of quicklime (containing 80% CaO) and alum in kg/day.

## Solution



(a) Alkalinity consumed =  $20 \text{ mg/L} \times 0.5 = 10 \text{ mg/L}$  as  $\text{CaCO}_3$

Natural alkalinity =  $4.0 \text{ mg/L}$  as  $\text{CaCO}_3$

Amount of alkalinity that has to be added in form of  $\text{CaO} = 10 - 4 = 6 \text{ mg/L}$  as  $\text{CaCO}_3$

Dose of lime  $\text{CaO}$  required =  $(28/50) \times 3.36 \text{ mg/L}$

Note : EW of  $\text{CaO} = 28$

(b) Quality of quicklime required =  $3.36 / 0.8 = 4.2 \text{ mg/L}$

Total quantity of quicklime needed for  $35,000 \text{ m}^3 / \text{day} = 35000 \text{ m}^3 / \text{day}$   
 $\times 4.2 \text{ g/m}^3$   
 $= 147,000 \text{ g/day}$   
 $= 147 \text{ kg/day}$

Total quantity of alum required =  $35,000 \text{ m}^3/\text{day} \times 20 \text{ g/m}^3 = 700,000 \text{ g/d}$   
 $= 700 \text{ kg/d}$

## Jar Test

- To determine the optimum coagulant dosage
- Test repeated with every significant change of raw water quality
- Results used to determine quality of coagulant used in water treatment plant.



## Method

1. Fill four to six beakers with 1 litre raw water sample
2. Add various coagulant dose into each beaker
3. Mix rapidly for 30 to 60 seconds
4. Mix slowly for 15 minutes
5. Stop mixing and let flocs settle.  
Determine the optimum dosage by observation
6. To determine the optimum pH, repeat step 5 but vary the pH in each beaker.

## Example 1

From jar test results, it was found that the optimum alum dose was 20 mg/L. Determine the quantity of alum required for a month's supply for a 20 MLD water treatment plant.

## Solution

1 litre require 20 mg

1 m<sup>3</sup> require  $20 \times 10^3$  mg or 20 g

20 MLD or 20000 m<sup>3</sup> require  $20 \text{ g} \times 20000$   
or 400 kg

For 1 month, alum required

=  $400 \text{ kg} \times 30$

= 12000 kg

## Example 2

A water treatment plant treats  $43200 \text{ m}^3$  of water in a day. Based on Jar Test, the optimum dosage obtained when 50 mL of 1g/L is added into 2 L of water. Find

- i- the amount of alum required (kg) in a month
- ii- the flow rate of the alum solution ( $\text{m}^3/\text{day}$ ).

## Solution

**Alum concentration = 1g/L**

**Dosage = 50 mg/2L = 25 mg/L**

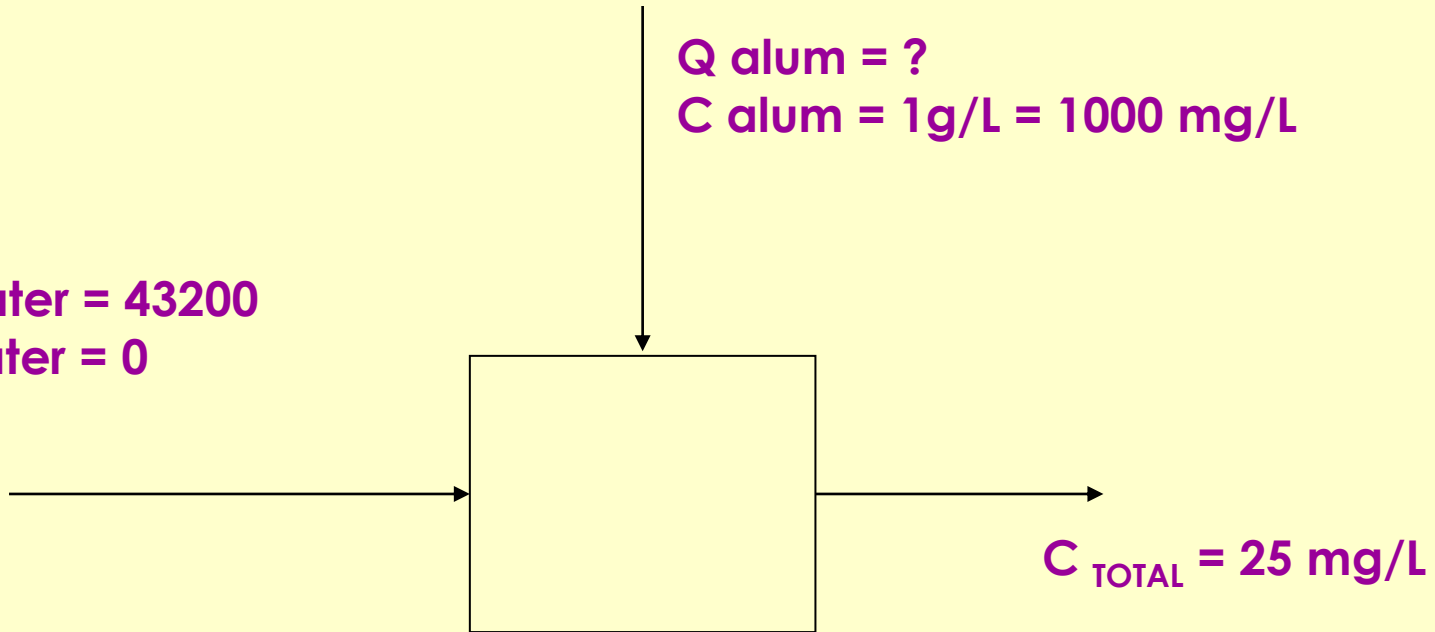
**i- alum required**

**= 43200 m<sup>3</sup>/day x 25mg/L**

**= 32400 kg/month**

$Q_{\text{alum}} = ?$   
 $C_{\text{alum}} = 1 \text{ g/L} = 1000 \text{ mg/L}$

$Q_{\text{water}} = 43200$   
 $C_{\text{water}} = 0$



$C_{\text{TOTAL}} = 25 \text{ mg/L}$


$$Q_w C_w + Q_a C_a = (Q_w + Q_a) C_T$$

$$Q_a \times 1000 = (43200 + Q_a) 25$$

$$1000 Q_a = 1080000 + 25 Q_a$$

$$Q_a = 1108 \text{ m}^3/\text{day}$$

# Removal of Dissolved Solids

## (1) Softening

- Purpose: to remove metallic ions that cause hardness (particularly  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$ )
- Hardness:
  - *Carbonate hardness* : bicarbonate and carbonate salts.  
[e.g.  $\text{Ca}(\text{HCO}_3)_2$ ,  $\text{CaCO}_3$ ,  $\text{Mg}(\text{HCO}_3)_2$ ,  $\text{MgCO}_3$ ].
  - *Non-carbonate hardness* : non-carbonate salts.  
[e.g.  $\text{CaSO}_4$ ,  $\text{CaCl}_2$ ,  $\text{MgSO}_4$ ,  $\text{MgCl}_2$ ].

## Types of Softening Processes

### (1) Precipitation Softening (Lime-Soda Softening)

- Lime,  $\text{CaO}$ : When slaked with water,  $\text{Ca}(\text{OH})_2$  (lime slurry) is formed:





CaO can be obtained by heating  $\text{CaCO}_3$ :



- Forms of lime:

- *Quicklime* (granules): contains a minimum of about 90%  $\text{CaO}$  + impurities.
- *Hydrated lime* (powder): contains about 68% of  $\text{CaO}$ .

- Soda ash,  $\text{Na}_2\text{CO}_3$ : grayish-white powder containing at least 98%  $\text{Na}_2\text{CO}_3$ .

## Chemistry of Precipitation Softening

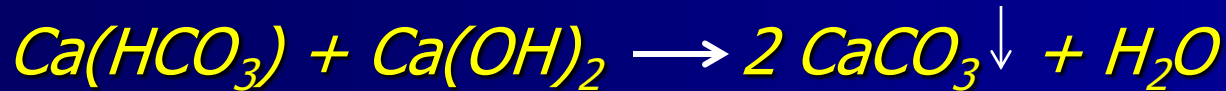
- Lime is added to remove carbonate hardness by converting soluble bicarbonate ( $\text{HCO}_3^-$ ) to insoluble carbonate ( $\text{CO}_3^{--}$ ).
- Soda ash is added to remove non-carbonate hardness.
- $\text{CO}_2$  is applied after lime treatment to lower the pH (re-carbonation).

- Softening Reactions:

- × Lime reacts with free CO<sub>2</sub> forming CaCO<sub>3</sub> precipitates:



- × Lime reacts with calcium bicarbonate forming CaCO<sub>3</sub> precipitate:



- × Lime reacts with magnesium bicarbonate forming Mg(OH)<sub>2</sub> precipitates:



- × Lime reacts non-bicarbonate magnesium salts:



No softening results from the last two reactions because CaSO<sub>4</sub> and CaCl<sub>2</sub> are formed.

- × Soda ash,  $\text{Na}_2\text{CO}_3$ , is added to remove  $\text{CaSO}_4$  and/or  $\text{CaCl}_2$  originally present in water and also that formed from previous reactions:



## Types of lime-soda softening

(A) Excess-lime softening. (B) Selective Calcium Removal. (C) Split-flow Softening.

### (A) Excess-Lime Softening

- Addition of lime raises the pH to about 10.3, which is enough to suppress the solubility of  $\text{CaCO}_3$ .
- But precipitation of  $\text{Mg}(\text{OH})_2$  requires a higher pH, and thus an excess amount of 35 mg/L of CaO is added to precipitate magnesium.

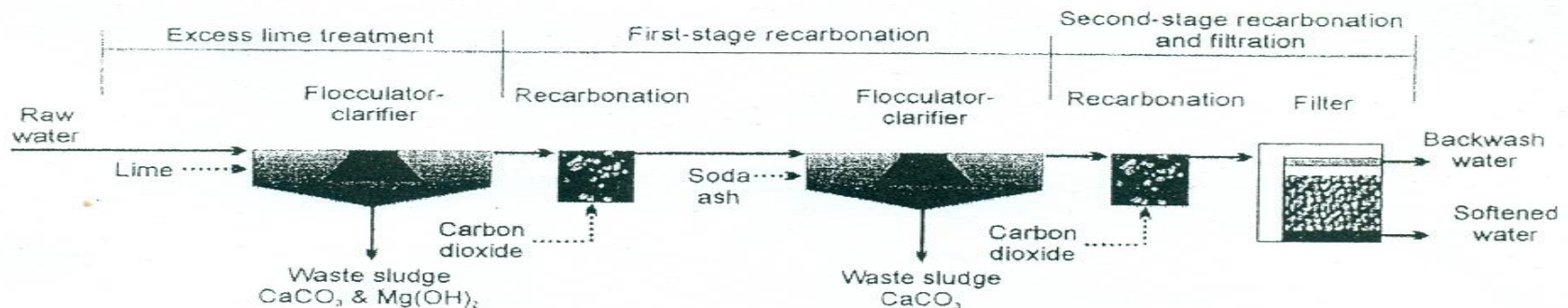
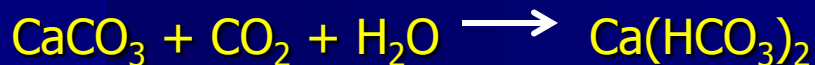
- Complete removal of hardness is not possible because of solubility limits of  $\text{CaCO}_3$  and  $\text{Mg(OH)}_2$  of about 40 mg/L as  $\text{CaCO}_3$  [30 mg/L of  $\text{CaCO}_3$  as  $\text{CaCO}_3$  + 10 mg/L of  $\text{Mg(OH)}_2$  as  $\text{CaCO}_3$ ]. That is, a hardness of about 40 mg/L as  $\text{CaCO}_3$  remains in the softened water.

## Re-carbonation (addition of $\text{CO}_2$ after lime treatment)

- Stage One:  $\text{CO}_2$  is added to lower the pH to about 10.3 and convert the dissolved excess lime into solid  $\text{CaCO}_3$ :



- Stage Two:  $\text{CO}_2$  is added to reduce the pH to the range of 8.5 to 9.5 to convert most of the remaining carbonate to bicarbonates:



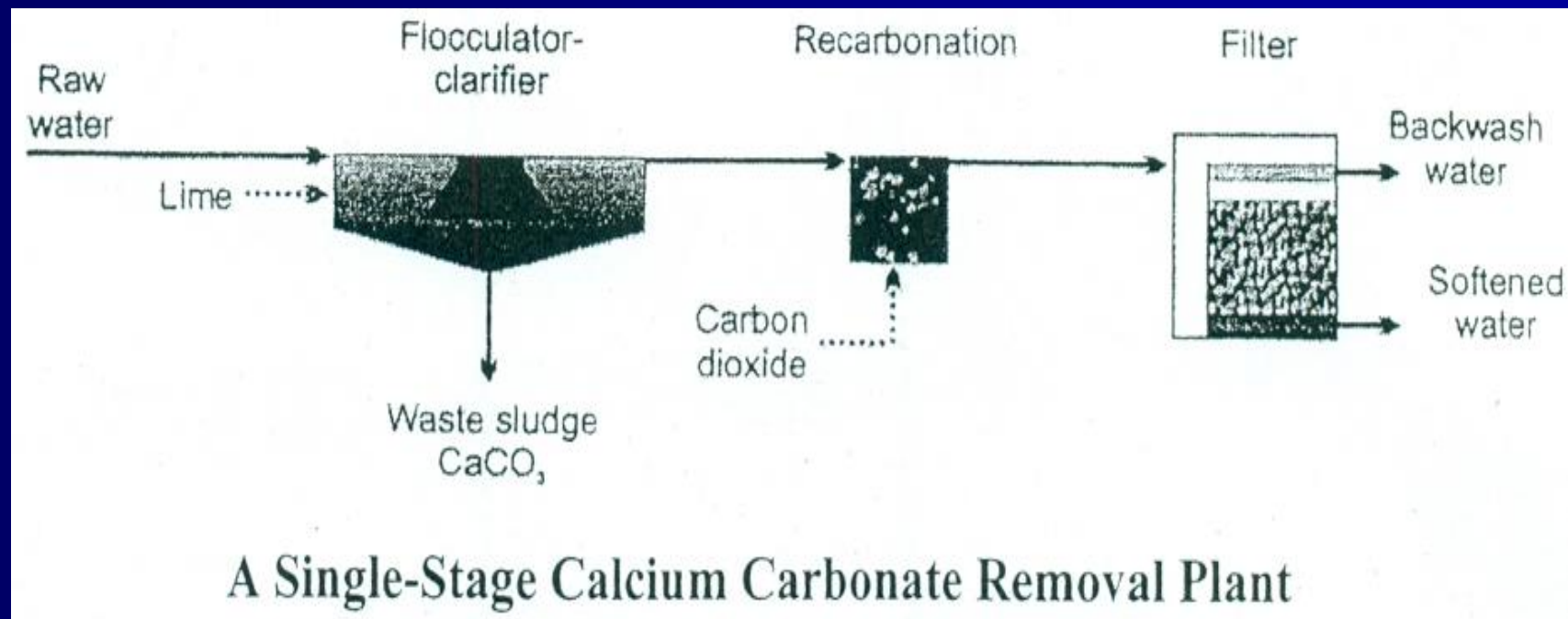
**Two-Stage Excess Lime Softening**

## **(B) Selective Calcium removal:**

**\* Used to soften a water low in magnesium hardness (less than 40 mg/l as  $\text{CaCO}_3$ ).**

**\* Lime is added to remove the calcium hardness without adding excess lime.**

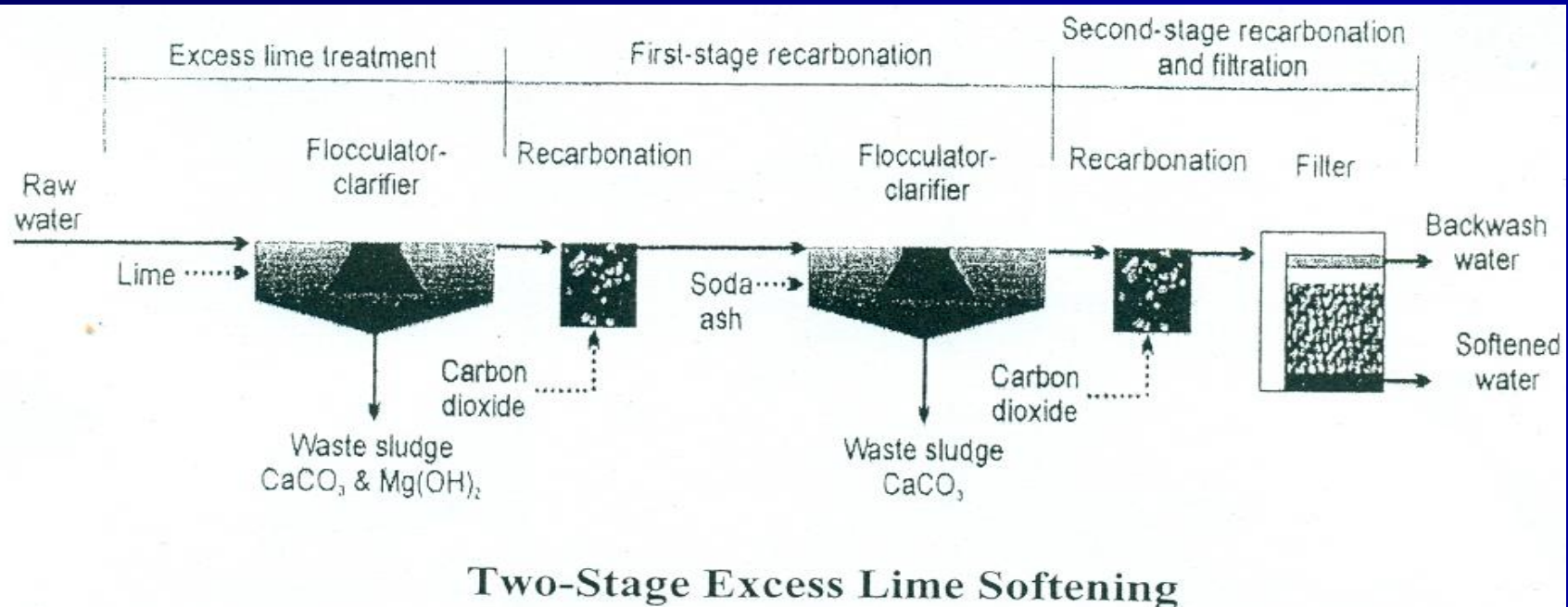
**\*  $\text{CO}_2$  is added to reduce scalling of the filter media and to produce stable softened water (re-carbonation).**





# (C) Split Flow Softening

- Raw water is divided into two streams.
- The larger portion is given excess lime treatment in the first stage of treatment (to remove both Ca and Mg hardness).
- In the second stage, soda is added to the mixture of the split flow (by-pass flow) and the treated water.
- Excess lime used in the first stage is used now to precipitate the Ca hardness in the by-pass flow (thus, no need for re-carbonation).
- The desired level of Mg in the softened water can be controlled.
- Used when the desired hardness is  $> 40 \text{ mg/l as CaCO}_3$ .



## Softened Sludge

Contains  $\text{CaCO}_3$  and  $\text{Mg}(\text{OH})_2$ .

$\text{CaCO}_3$  compacts readily.

$\text{Mg}(\text{OH})_2$  gelatinous and does not consolidate well by gravity settling.

Settled solids concentrations range from 2% to 15% depending on the Ca to Mg precipitate.

## Other benefits of Chemical Softening

Disinfection of water (due to high pH).

Removal of heavy metals (due to high pH).

**Example:**

Water defined by the following analysis is to be softened by excess lime treatment. Assume that the practical limit of hardness removal for  $\text{CaCO}_3$  is 30 mg/l, and that of  $\text{Mg}(\text{OH})_2$  is 10 mg/l as  $\text{CaCO}_3$ .

$\text{CO}_2$	= 8.8 mg/l
$\text{Ca}^{++}$	= 40.0 mg/l
$\text{Mg}^{++}$	= 14.7 mg/l
$\text{Na}^+$	= 13.7 mg/l
$\text{Alk}(\text{HCO}_3^-)$	= 135 mg/l as $\text{CaCO}_3$
$\text{SO}_4^{=}$	= 29.0 mg/l
$\text{Cl}^-$	= 17.8 mg/l

- Sketch a meq/l bar graph, and list the hypothetical combinations of chemical compounds in solution.
- Calculate the softening chemicals required, expressing lime dosage as  $\text{CaO}$  and soda ash as  $\text{Na}_2\text{CO}_3$ .
- Draw a bar graph for the softened water before and after recarbonation. Assume that half the alkalinity in the softened water is in the bicarbonate form.

**Solution:**

Components	mg/l	Equivalent Weight	meq/l
$\text{CO}_2$	8.8	22.0	0.40
$\text{Ca}^{++}$	40.0	20.0	2.00
$\text{Mg}^{++}$	14.7	12.2	1.21
$\text{Na}^+$	13.7	23.0	0.60
Alk	135	50.0	2.70
$\text{SO}_4^{=}$	29.0	48.0	0.60
$\text{Cl}^-$	17.8	35.0	0.51



0.0	2.00	3.21	3.81
CO <sub>2</sub>	Ca <sup>++</sup>	Mg <sup>++</sup>	Na <sup>+</sup>
0.4	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>=</sup>	Cl <sup>-</sup>
0.0	2.70	3.3	3.81

### Meq/l bar graph for the raw water before treatment

Components	MEQ/L	Application Equation	Lime Meq/l	Soda Ash Meq/l
CO <sub>2</sub>	0.40	7-15	0.40	0
Ca(HCO <sub>3</sub> ) <sub>2</sub>	2.00	7-16	2.00	0
Mg(HCO <sub>3</sub> ) <sub>2</sub>	0.70	7-17	1.40	0
MgSO <sub>4</sub>	0.51	7-18 & 7-19	<u>0.51</u>	<u>0.51</u>
			4.31	0.51

Lime dosage = stoichiometric quantity + excess lime (35 mg/l CaO)

$$= 4.31 \times 28 + 35 = 156 \text{ MG/L CaO}$$

[note: eq. wt of CaO = (40 + 16) / 2 = 28]

Soda ash dosage = 0.51 x 53 = 27 mg/l Na<sub>2</sub> CO<sub>3</sub>

[note: eq. wt. of Na<sub>2</sub>CO<sub>3</sub> = (23 x 2 + 12 + 16 x 3) / 2 = 106/2 = 53]

	0.0	0.6	0.8	1.91
Ca <sup>++</sup>	Ca <sup>++</sup>	Mg <sup>++</sup>	Na <sup>+</sup>	
OH <sup>-</sup>	OH <sup>-</sup>	CO <sub>3</sub> <sup>=</sup>	SO <sub>4</sub> <sup>=</sup>	Cl <sup>-</sup>

**1.25 of excess lime      0.0      0.2                      0.8                      1.40                      1.91**

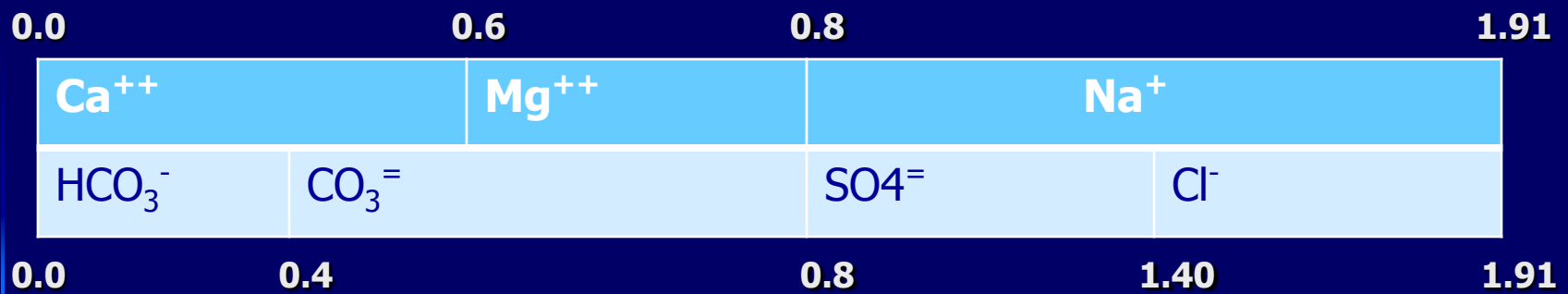
**meq/L bar graph for water after excess lime softening but before carbonation**

Note on the above Figure:

- Excess lime = 35 mg/L CaO  $\longrightarrow$   $35/28 = 1.25$  meq/L
- Practical limits for hardness reduction:
  - \* 30 mg/L of CaCO<sub>3</sub>  $\longrightarrow$   $30/50 = 0.6$  meq/L
  - \* 10 mg/L of Mg(OH)<sub>2</sub> as CaCO<sub>3</sub>  $\longrightarrow$   $10/50 = 0.2$  meq/L

Thus, alkalinity after softening and before re-carbonation consists of 0.2 meq/L of OH<sup>-</sup> associated with Mg and remaining 0.6 meq/L in the CO<sub>3</sub><sup>=</sup> form.

- Na<sup>+</sup> : 0.6 meq/L originally present in water + 0.51 meq/L due to Na<sub>2</sub>CO<sub>3</sub> addition = 1.11 meq/L
- SO<sub>4</sub><sup>=</sup> and Cl<sup>-</sup> meq/L are unchanged by the softening process.



**meq/L bar graph for the softened water after re-carbonation**

**This bar graph is based on the assumption that half of the remaining alkalinity is in the bicarbonate form. Recarbonation converts the excess hydroxide ions to carbonate ions and converts the carbonate ions to bicarbonate ions.**

**Re-Carbonation:**

**First Stage: CO<sub>2</sub> is added to convert excess OH<sup>-</sup> to carbonate ions:**



**The amount of CO<sub>2</sub> = (1.25 + 0.2 ) X 22 = 31.9 mg/l**

**Thus, the total amount of co<sub>2</sub> required for re-carbonation = 31.9 + 8.8 = 40.7 mg/l**

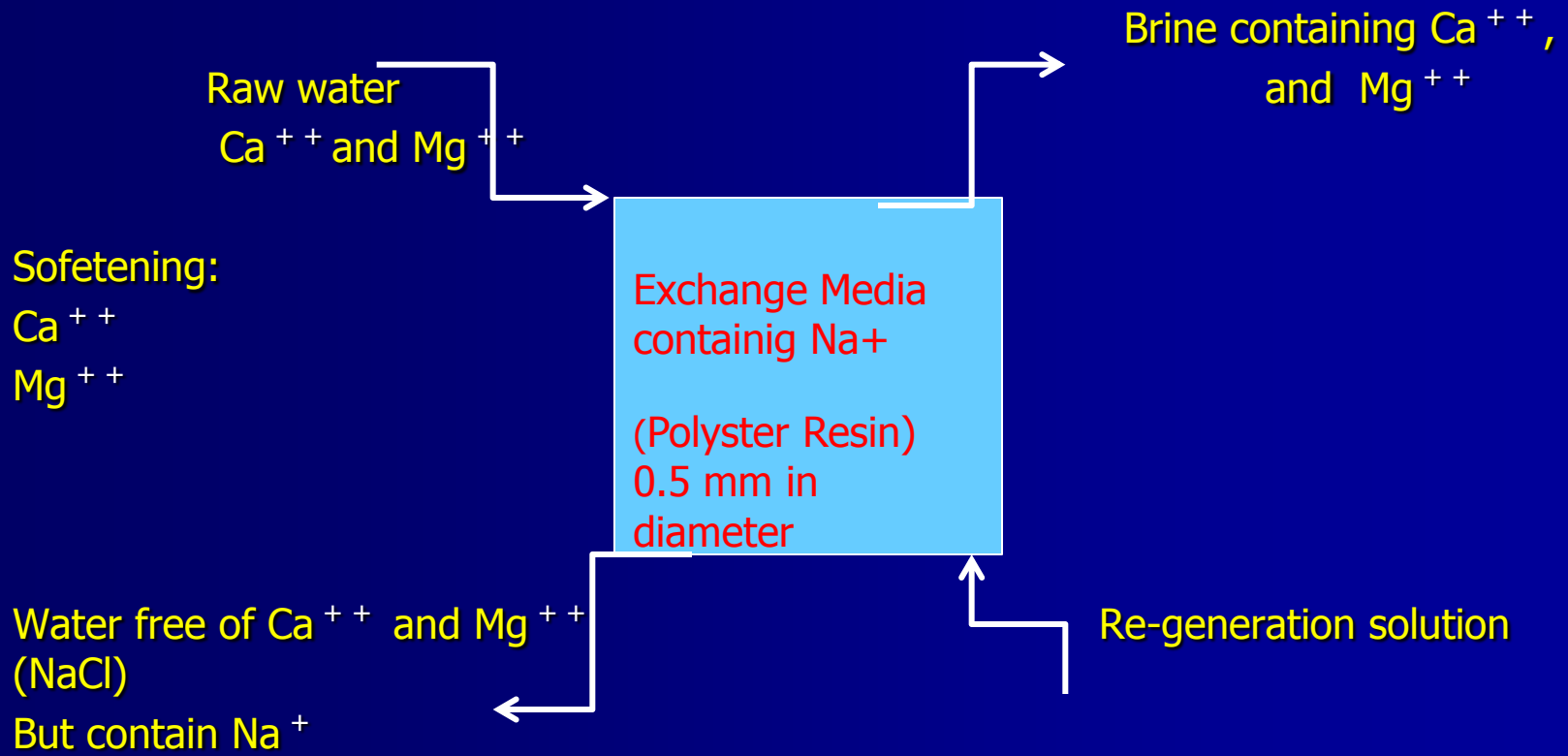
# Cation-Exchange Softening

- Hard water is passed through a filter bed containing cation-exchange media (resins) where  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$  are absorbed on the media and an equivalent amount of  $\text{Na}^+$  is released into solution.

## Note:

Resin: insoluble polymers containing fixed cations or anions capable of reversible exchange with mobile ions in the solution with which they are brought into contact.

When the media is exhausted, a strong sodium chloride solution ( $\text{NaCl}$ ) is passed through the bed to regenerate the media with  $\text{Na}^+$ .



## Desalination (Removal of salt)

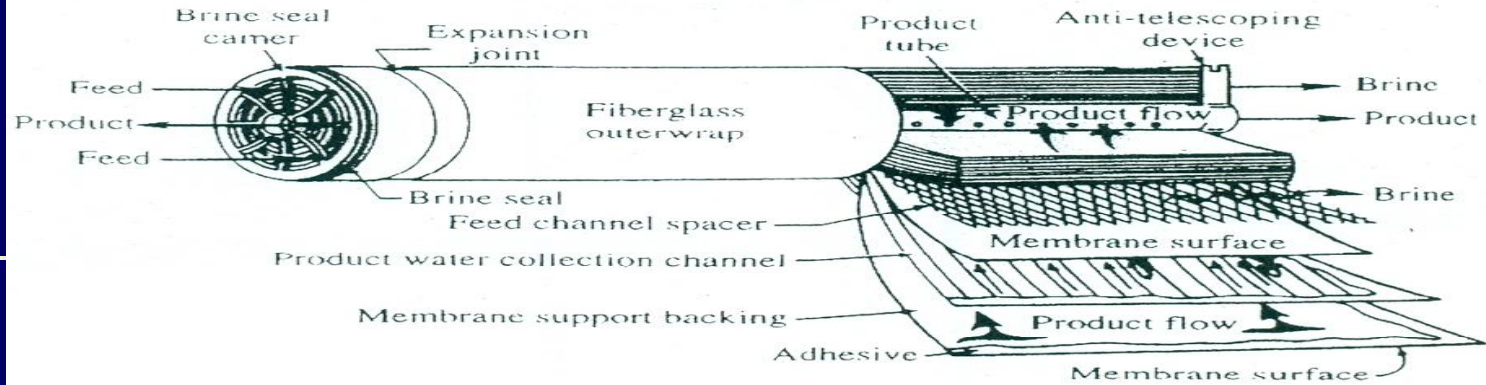
- Processes used for desalination / demineralization
- Distillation – Reverse Osmosis – Ion exchange - Electrodialysis
- Salinity of wastewater  $\approx 35,000$  mg/L (mostly sodium chloride).
- Salinity of brackish groundwater  $> 1000$  mg/L
- Reverse Osmosis
  - \* Osmosis: the process of diffusion/transfer of a solvent (water) through a semi-permeable membrane from a solution of a lower to one of a higher concentration.
  - \*Reverse Osmosis: The forced passage of water through a semi-permeable membrane against the natural osmotic pressure to accomplish separation of water and ions.

## \*Membranes

- 100-150 microns (skin layer < 1 micron + porous support structure).
  - Size of pores: 0.001 microns (theoretical).
  - Membrane material: cellulose acetate, polyamide
- 
- **Membrane configurations / modules:**
    - Spiral-wound module

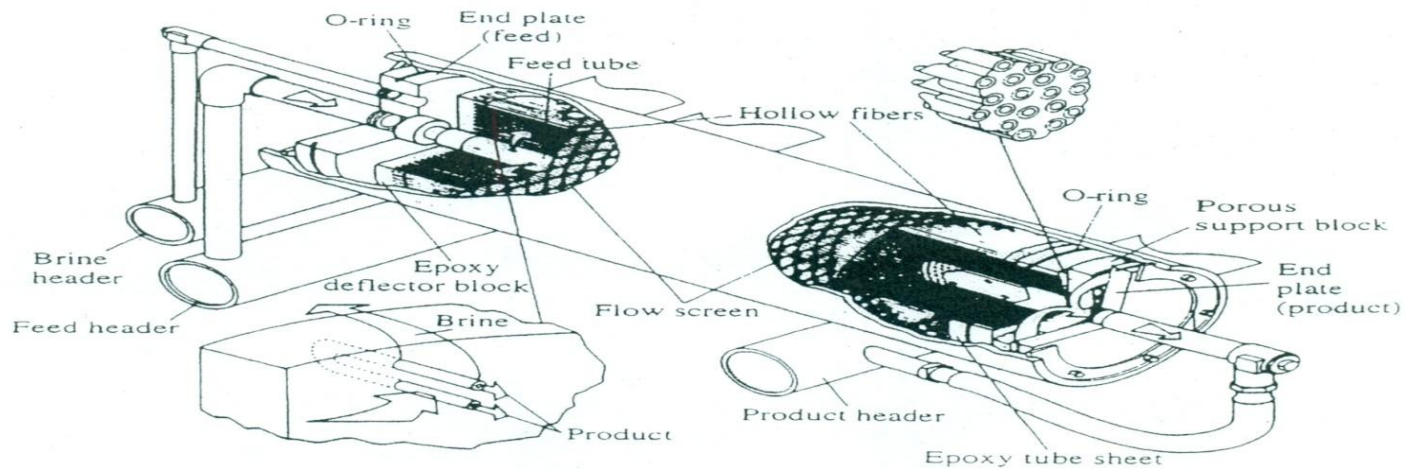
## Membrane configurations / modules:

### Spiral-wound module



## Spiral-wound module membrane

### Hollow fiber module



- Outside diameter of hollow fibers = 80 – 100 microns

## Hallow fiber module membrane





Full Scale  
Reverse  
Osmosis units



Full Scale  
Reverse Osmosis  
plants



## **\* Operating pressure of RO a system:** 350-1500 psi (24-100 bar)

Note: Osmotic pressure of sea water = 350 psi

Osmotic pressure of groundwater is much less (because TDS is low)

### **\* Pre-treatment**

- Saline water fed to RO system must be free of SS, organic matter, excessive hardness, and Fe and Mn to prevent fouling and scaling of membranes.
- Pre-treatment Methods:
  - Coagulation and filtration: to remove turbidity, Fe and Mn.
  - Softening: to remove hardness.
  - Adsorption (by AC): to remove organics.
  - Acidification (addition of  $\text{H}_2\text{SO}_4$ ): to reduce pH to less than 6 to convert  $\text{HCO}_3^-$  to  $\text{CO}_2$  gas in order to reduce  $\text{CaCO}_3$  scale and oxidation of Fe and Mn.
  - Addition of scale inhibitors (e.g. hexametaphosphate): to prevent chemical scaling.

### **\* Post-treatment**

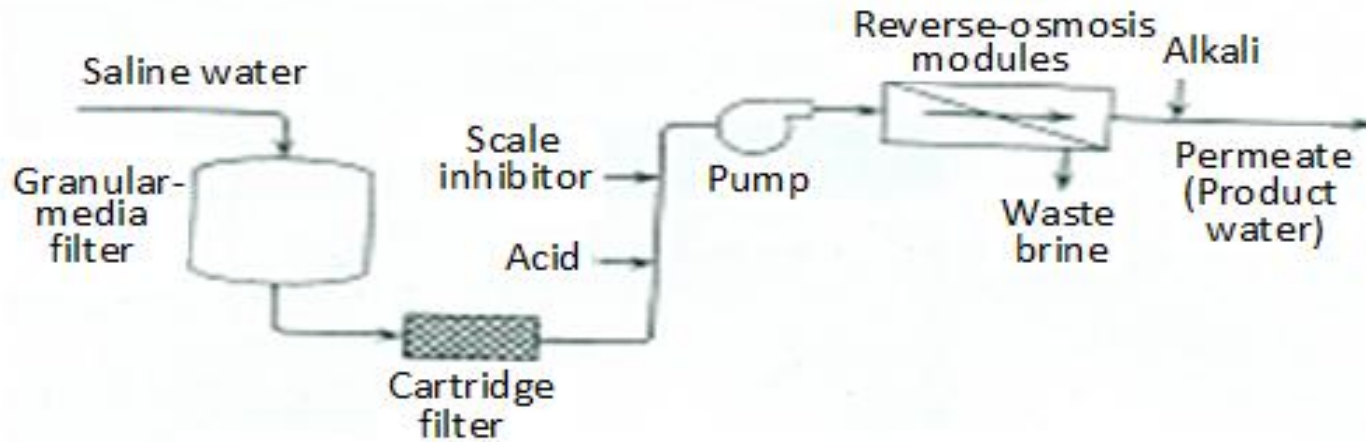
- RO product (permeate) must be stabilized.
- Post-treatment methods:
  - Aeration: to remove  $\text{CO}_2$
  - Addition of lime and soda ash: to adjust pH to about 8.0.

### **\* Membrane Cleaning**

- Flushing with acid rinses and cleaning agents to remove build-up of salts, metal ions, organic matter or biological growths.

## \* Reject Brine

- Reject = 10% to 30% of the feed water.



**Flow Diagram of a Basic Reverse Osmosis System**

# FLOCCULATION

The objective of flocculation is to provide for an increase in the number of contacts between coagulated particles suspended in water by gentle and prolonged agitation. Agitation results in collision of the particles leading to the formation of floc large enough to settle in a sedimentation tank.

# Flocculation Theory

- The flocculation process relies on turbulence to promote collisions between destabilized particles to form large and dense flocs.
- Design parameter for flocculation is **Camp Number,  $Gt$**  ( a dimensionless number )

where

$G$  = velocity gradient,  $s^{-1}$  ( 20 – 75  $s^{-1}$  )

$t$  = time, s ( 10 – 60 min )

$Gt$  = 12 000 – 270 000

## Types of flocculation

Flocculation can be achieved by mechanical devices or hydraulic methods. Hydraulic methods are used most often in small plants. Mechanical flocculators cover a broad range of configurations.

# Mechanical Flocculation

## Advantages

- Flexibility of control
- Reduction in amount of chemicals used
- Less head loss
- Better floc formation if properly adjusted

## Disadvantages

- Low velocity around the shaft
- Dead spaces in corners and possibility of short circuiting
- High operation and maintenance cost

## Design detail

Power = Force x Velocity

$$P = F_D \times v_p \quad \text{—————} \quad (1)$$

where

P = power input, Watt or Nm/s

$F_D$  = drag force on paddles, N

$v_p$  = velocity of paddles (velocity relative to the water), m/s

$$F_D = \frac{1}{2} C_D A_p v_p^2 \rho \quad (2)$$

where

$C_D$  = coefficient of drag, 1.8 for flat blades

$A_p$  = area of paddle blades,  $m^2$

$\rho$  = density of water,  $kg/m^3$



$$P = G^2 \mu \nabla$$

$$P = G^2 \mu \nabla \quad (3)$$

where

$G$  = velocity gradient,  $s^{-1}$

$\mu$  = dynamic viscosity,  $Ns/m^2$

$\nabla$  = volume of mixing tank,  $m^3$

Therefore

$$P = \frac{C_D A_P (vp)^3 \rho}{2} \text{ ————— (4)}$$

## Example 1 :

A 20 MLD water treatment plant has two mechanical flocculating tanks each having a retention time of 35 minutes.

Based on the information below, answer the following questions:

Length:Width Ratio	=	4:1
Depth of water in tank	=	3.0 m
Hydraulic gradient	=	$50 \text{ s}^{-1}$
Dynamic viscosity	=	$0.798 \times 10^{-3} \text{ kg/ms}$
Velocity of paddle	=	$0.4 \text{ m/s}$
Coefficient of drag	=	1.8

- Determine the length and width of the flocculating tank
- Calculate the power required for each tank
- Find the area of each plate if the flocculator has 3 paddles and every paddle has 3 plates.

**Solution:**

a) Volume of each tank =  $\frac{1}{2} \times 20000 \times \frac{35}{60 \times 24} = 243 \text{ m}^3$

Surface area =  $243/3$

$$= 81 \text{ m}^2$$

Let width be  $x$ . Hence length is  $4x$ .

Therefore,  $4x^2 = 81$

$x = 4.5 \text{ m}$

$$4x = 18.0 \text{ m}$$

Hence, length is 18.0 m and width is 4.5 m.

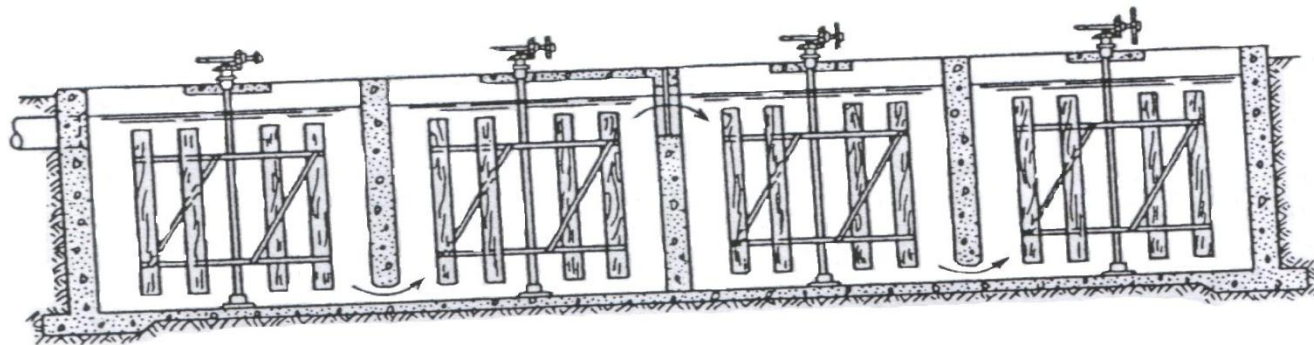
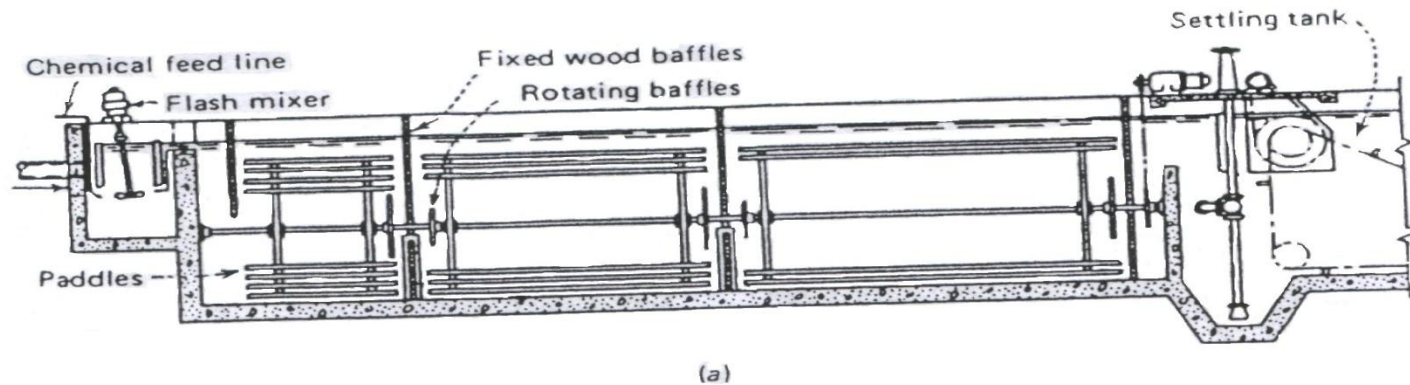
b) Power required for each tank  $= G^2 \mu V$   
 $= (50)^2 \times 0.798 \times 10^{-3} \times 50$   
 $= 485 \text{ W}$

$$c) \quad P = \frac{C_D A_P (v_P)^3 \rho}{2}$$

$$485 = \frac{1.8 A_P (0.5)^3 1000}{2}$$

$$A_P = 8.42 \text{ m}^2$$

$$\text{Area of each plate} = \frac{8.42}{3 \times 3} = 0.94 \text{ m}^2$$



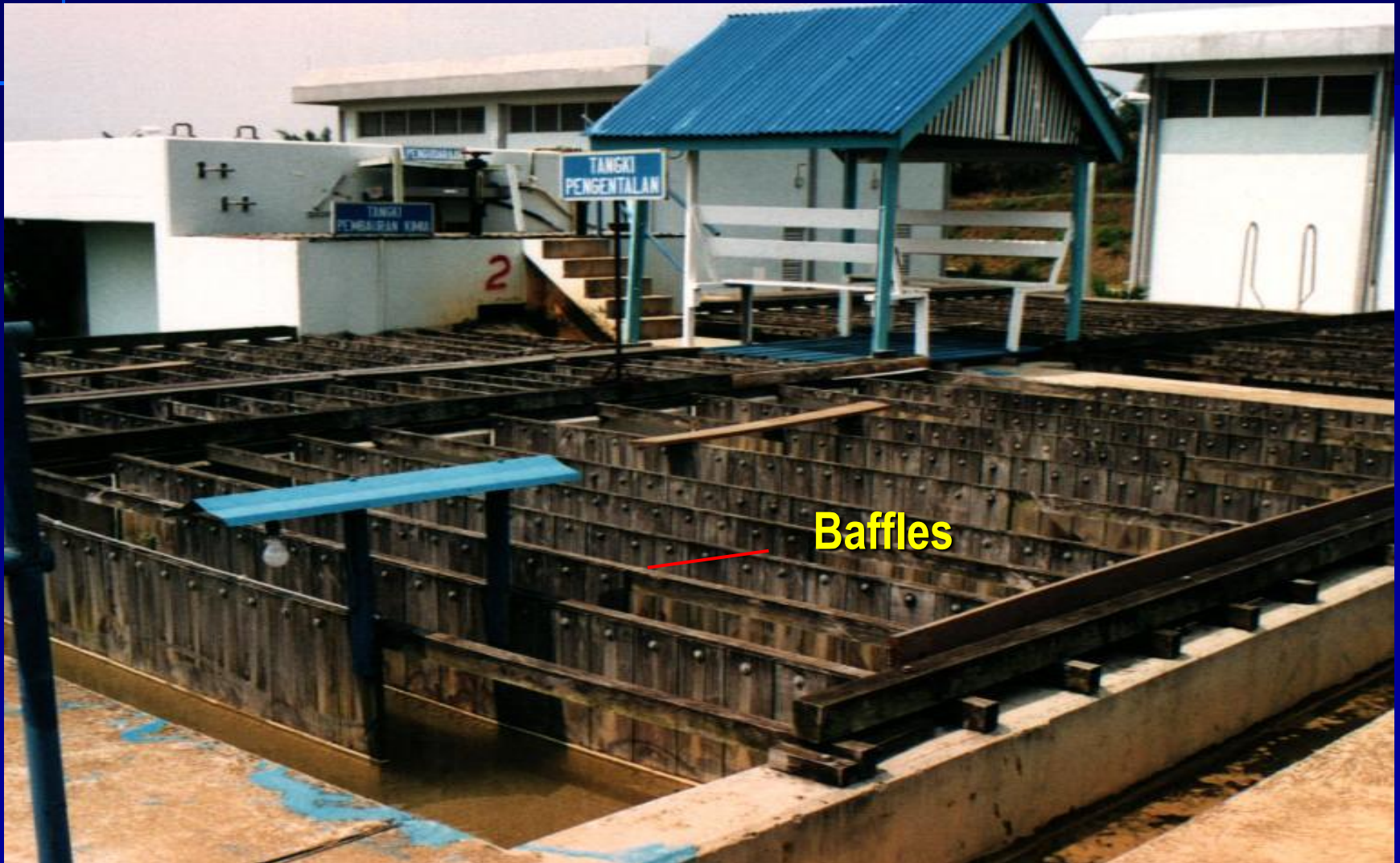
**Flocculation basins (a) Horizontal paddles (b) Vertical paddles**

# Hydraulic Flocculation

- Baffle type mixing basins are examples of hydraulic flocculation device. Baffles are provided in the basins which induce the required velocity gradients for achieving floc formation.



# Hydraulic Flocculation



## Advantages

- Simple to construct and operate
- Less chance of short-circuiting

## Disadvantages

- Cannot be easily adjusted
- Increase head loss

## Design details

1. Velocity in the channel should be 10 – 30 cm/s
2. Width of the channel should be minimum of 45 cm
3. Depth of flow should not be less than 1.0 m
4. The usual detention time is 20 – 30 minutes
5. Clear distance between baffle end and wall normally 1.5 times distance between baffles.
6. Minimum of two tanks to be built in any treatment plant.

## Example 2:

Design a baffle type basin of round the end type with the following data:

Daily quantity of water to be treated	=	15 MLD
Detention time	=	25 min.
Average velocity of flow	=	0.17 m/s
Distance between baffles	=	0.75 m
Thickness of each baffle	=	0.075 m
3 compartment, width of each compartment	=	3 m
Thickness of compartment wall	=	0.15 m

## Solution:

- Calculate the tank volume,  $\nabla$

$$\begin{aligned}\nabla &= Q \times t = 15 \times 10^6 \text{ L/day} \times 25 \text{ min} \\ &= 260 \text{ m}^3\end{aligned}$$

- For a detention time period of 25 min. and a velocity of flow of 0.17 m/s, the total distance of flow by water,

$$\begin{aligned}D &= t \times v \\ &= 25 \text{ min.} \times 0.17 \text{ m/s} = 255 \text{ m.}\end{aligned}$$

**Cross-sectional area of a channel  
between baffles,  $A_x$**

$$\begin{aligned} A_x &= V/D \\ &= 260/255 = 1.02 \text{ m}^2 \end{aligned}$$

**Depth of channel,  $d$**

$$\begin{aligned} &= A/(\text{distance between baffles}) \\ &= 1.02/0.75 \\ &= 1.36\text{m} \end{aligned}$$

The clear distance between baffle and the end of wall is taken as 1.5 times the distance between baffles;  $y$

$$\begin{aligned} y &= 1.5 \times 0.75 \\ &= 1.125 \text{ m} \end{aligned}$$

The effective length of each channel;  $P_e$

$$\begin{aligned} P_e &= 3 - y = 3 - 1.125 \\ &= 1.875 \text{ m} \end{aligned}$$

**No. of channels required for a flow length of 255 m**

$$= D/Pe = 255/1.875 = 136$$

**No. of channels for each compartment**

$$= 136/3 = 46$$

**Length of basin**

$$= (46 \times 0.75) + (45 \times 0.075) = 38 \text{ m}$$

**Width of basin**

$$= (3 \times 3) + (2 \times 0.15) = 9.3 \text{ m}$$

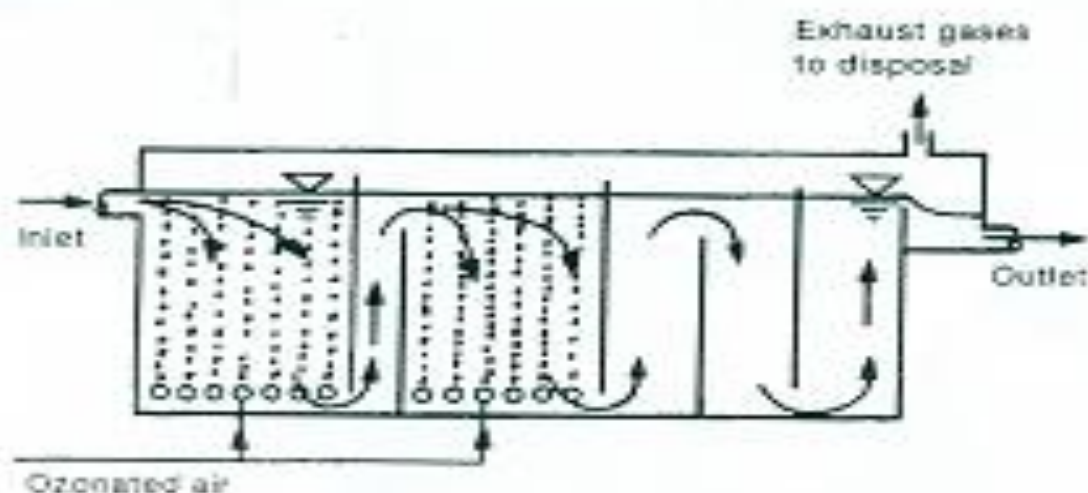


(c) If 36,000 liters of water are used to fill the main at a dosage of 50 mg/L, how many liters of hypochlorite solution are used?

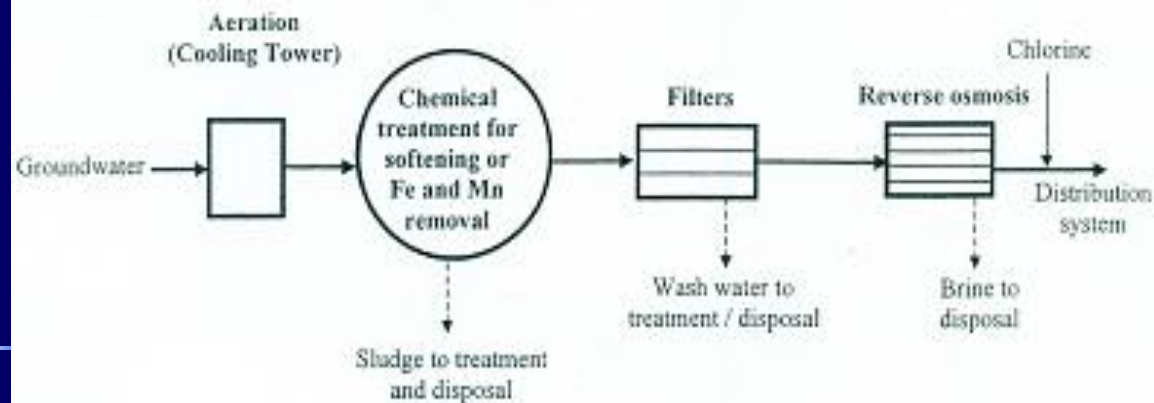
$$\text{Solution usage} = 36,000 \text{ L} \times (1 \text{ L} / 400 \text{ L}) = 90 \text{ Liters}$$

## 2) Ozonation

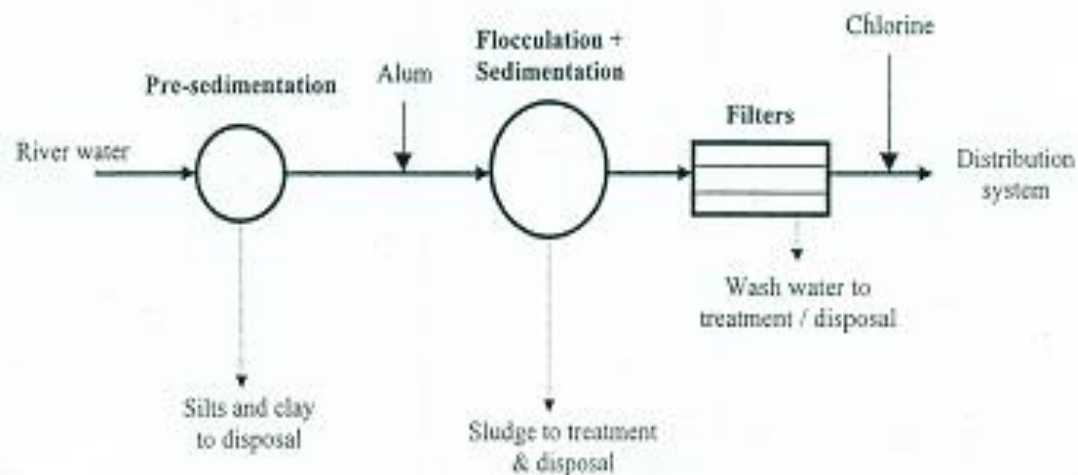
- $\text{O}_3$  decomposes in water to produce oxygen and free hydroxyl radicals ( $\text{HO}$  and  $\text{HO}_2$ ).
- Very strong oxidant (more effective than chlorine).
- Leaves no taste or odor.
- No residual is produced to protect water during distribution and transfer.
- Must be generated on site because it decays rapidly.
- More costly than chlorination.
- Ozone forms carcinogenic and toxic DBPs such as aldehydes (e.g. formaldehyde), various acids (e.g. acetic acid), and brominated byproducts in the presence of bromide (e.g. bromate ion, bromoform, brominated acetic acids), and others.



Cross contact tank composed of two compartments in series with ozonated air entering at the bottom, followed by three compartments for additional contact time.



**Schematic Diagram of Typical Groundwater Treatment Plant**



**Schematic Diagram of Typical River-Water Treatment Plant**