ES 200 Environmental Studies: Science & Engineering

Water Treatment Processes

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Drinking Water: Need for Purification

- **Surface water** from rivers, lakes and reservoirs cannot be directly used for drinking
  - Unacceptable turbidity & color, suspended solids, high levels of anions and heavy metals, trace organic contaminants
- **Groundwater (GW)** from aquifers may also require treatment to make it fit for consumption
  - High arsenic levels in GW causes chronic toxicity
  - High nitrate and fluoride levels in GW causes problems such as blue baby syndrome and dental & skeletal decay, respectively
  - Leachate generated from dumping grounds and unlined pits can contaminate GW
- **Pathogens in water**
  - Disease causing microorganisms reside in the intestine of warm-blooded animals
  - Contamination of water with sewage

Source of Drinking water

- Characteristics of a suitable drinking water source is defined by the Central Pollution Control Board (CPCB) in India
- **CPCB Classification:**
  - Classes A, B, C, D, E and others
    - A: Best Quality, Only disinfection required before drinking
    - C: Requires various types of treatment including disinfection
  - Defined in terms measurable parameters (Class A):
    - Class A: pH range-6.5-8.5; Dissolved oxygen > 6 mg/L; Count of Coliform Organisms (MPN) < 50 per 100 mL;
    - 5-day BOD at 20^oC < 2 mg/L

Is Your Tap Water Safe for Drinking ?

- Test if water quality parameters are within acceptable limits specified by authorized agencies
- **Indian Agencies**

  ICMR: Indian council of medical research

  BIS: Bureau of Indian standards

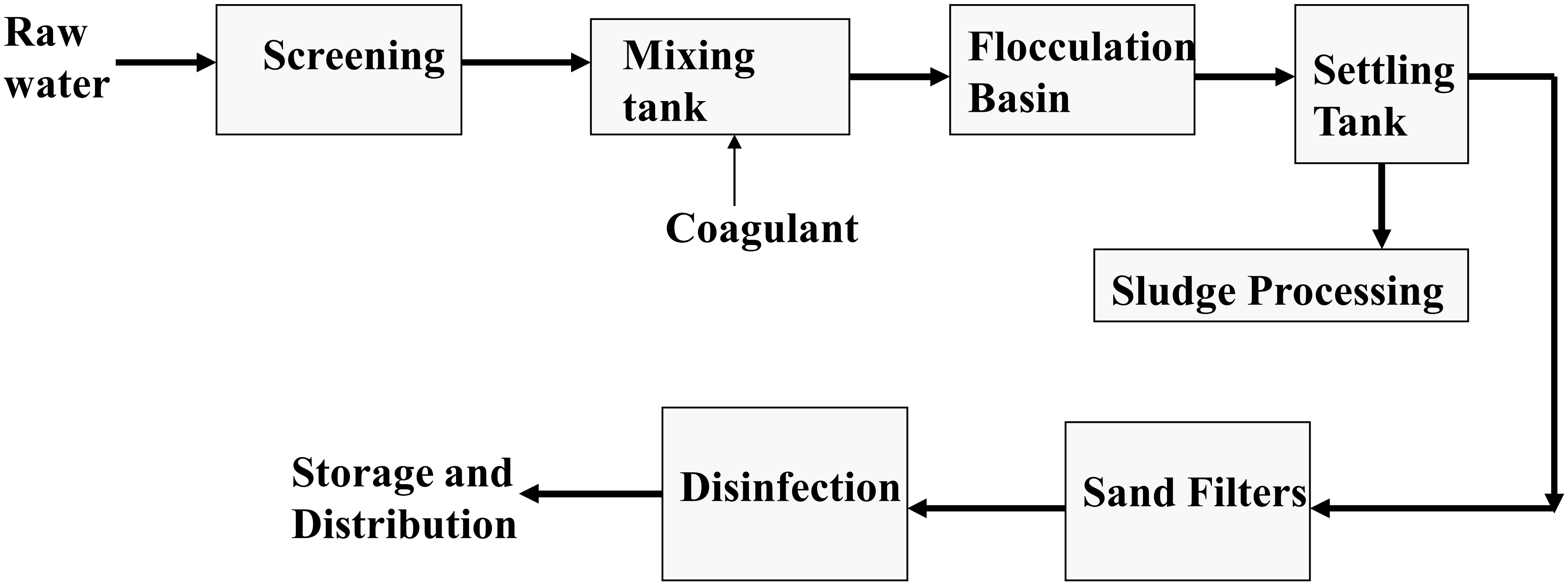
  CPCB: Central & State Pollution Control Boards formulates MINAS (Minimal National standards)
- **International Agencies**

  WHO: World Health Organisation

  US- EPA: Environment Protection Agency, USA

Conventional Water Treatment

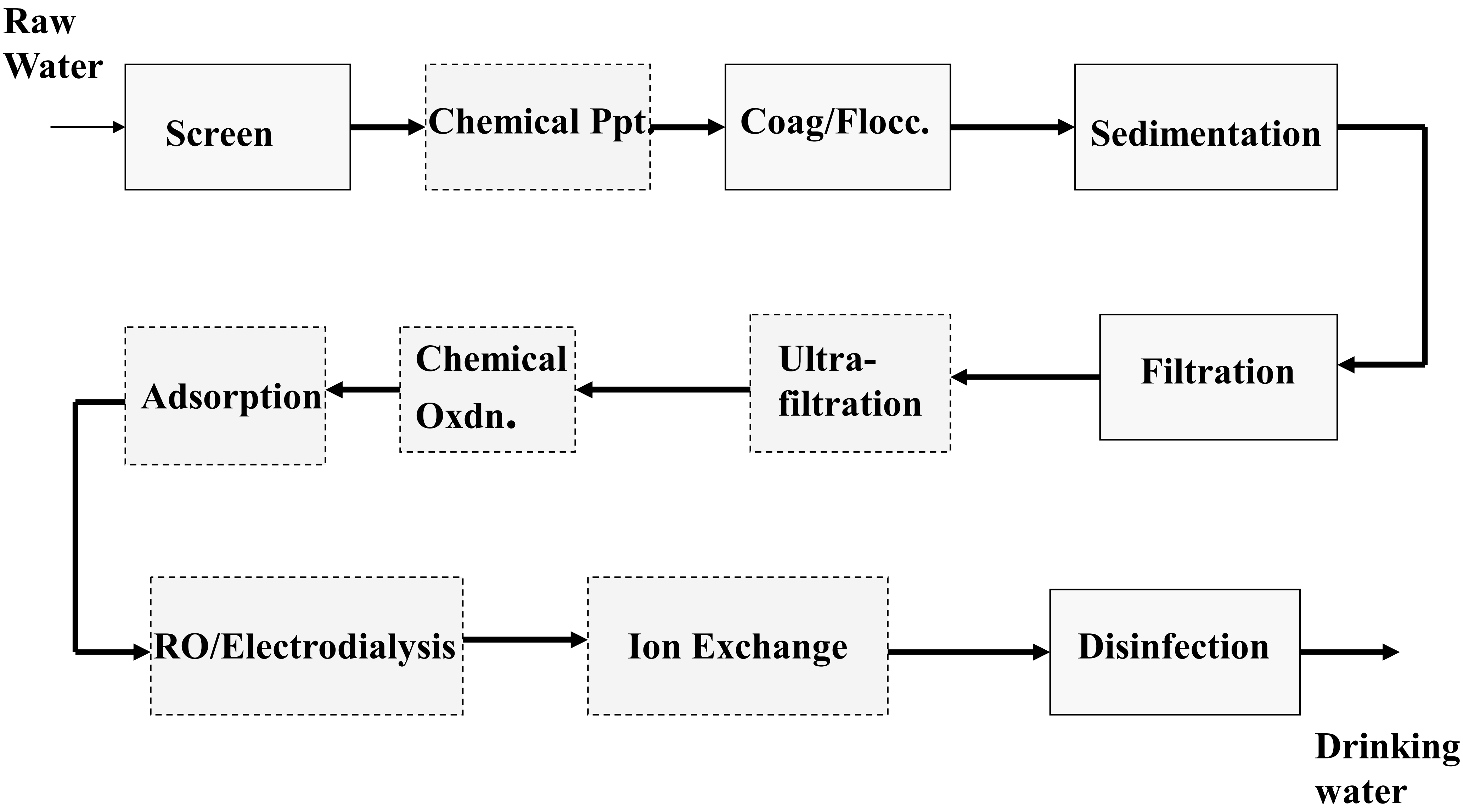
Raw water from lake / river is treated to meet the drinking water quality criteria using a series of unit operations



Conventional Treatment—Unit Operations

- **Screening:** Removes large floating and suspended objects
- **Coagulation**:Small colloidal solids are converted into large suspended particles by adding external agent
- **Flocculation**: Floc formation from destabilized colloidal particles by gentle mixing
- **Settling Tank**: Settling of flocs by gravity
- **Sludge Processing**: Processing of sludge / settled flocs
- **Filtration**: Removes suspended solids
- **Disinfection:** Removal of Pathogens

Advanced Treatment Process

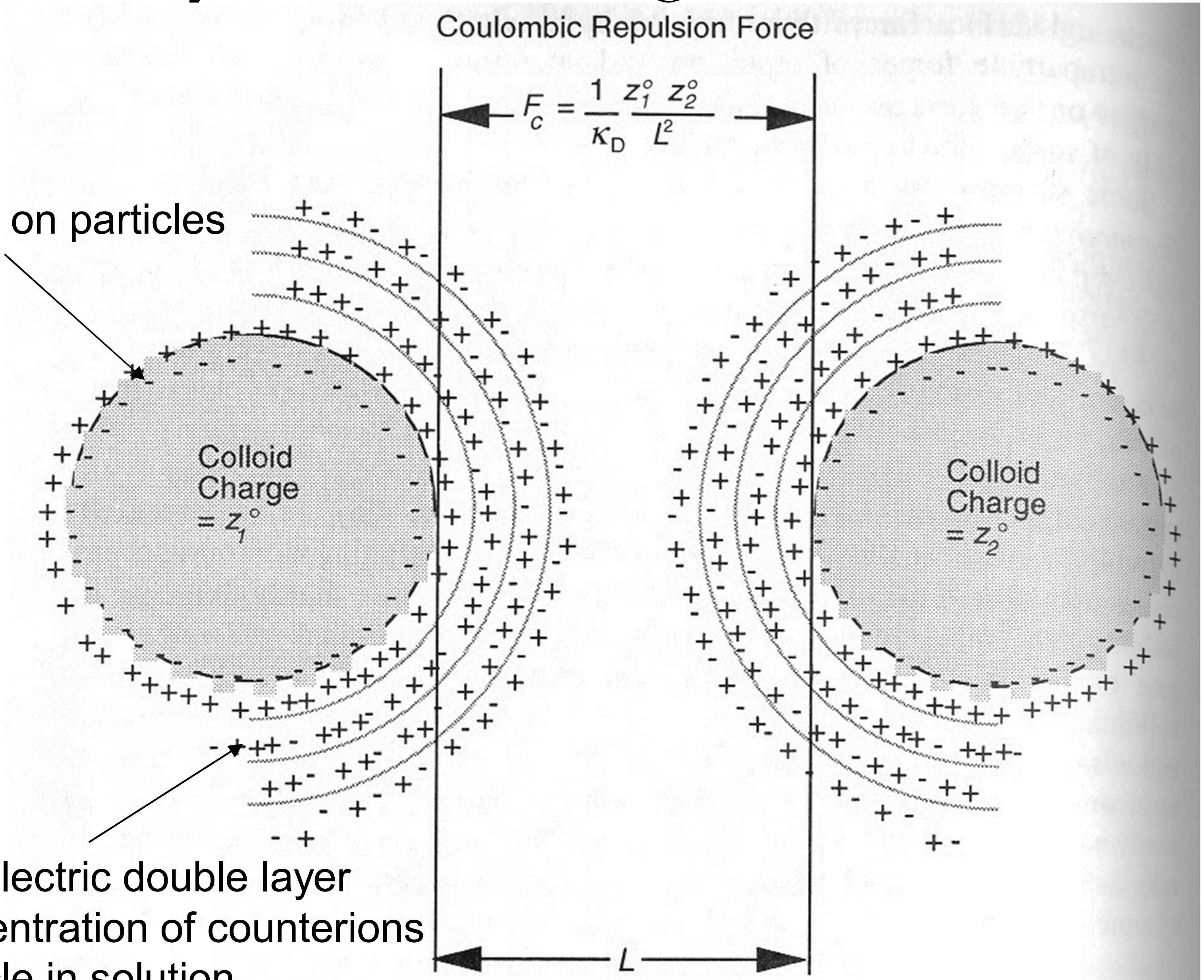


Coagulation & Flocculation

- Process for removal of colloids and color causing macromolecules
  - **Coagulation:** The chemical process of destabilization
    - Rapid mixing for a short period generates active species that achieves destabilization
  - **Flocculation:** The physical process of transport of particles to form flocs that can settle out, gentle mixing to promote contact

- **Colloids in water**
  - Size range: 0.001-1 µm; large surface to volume ratio
  - color causing macromolecules, clays, bacteria, viruses, proteins
  - Typically, negatively charged: like charges repel each other, hence colloidal particles resist aggregation

Mutual Repulsion: Charged Colloidal Particles

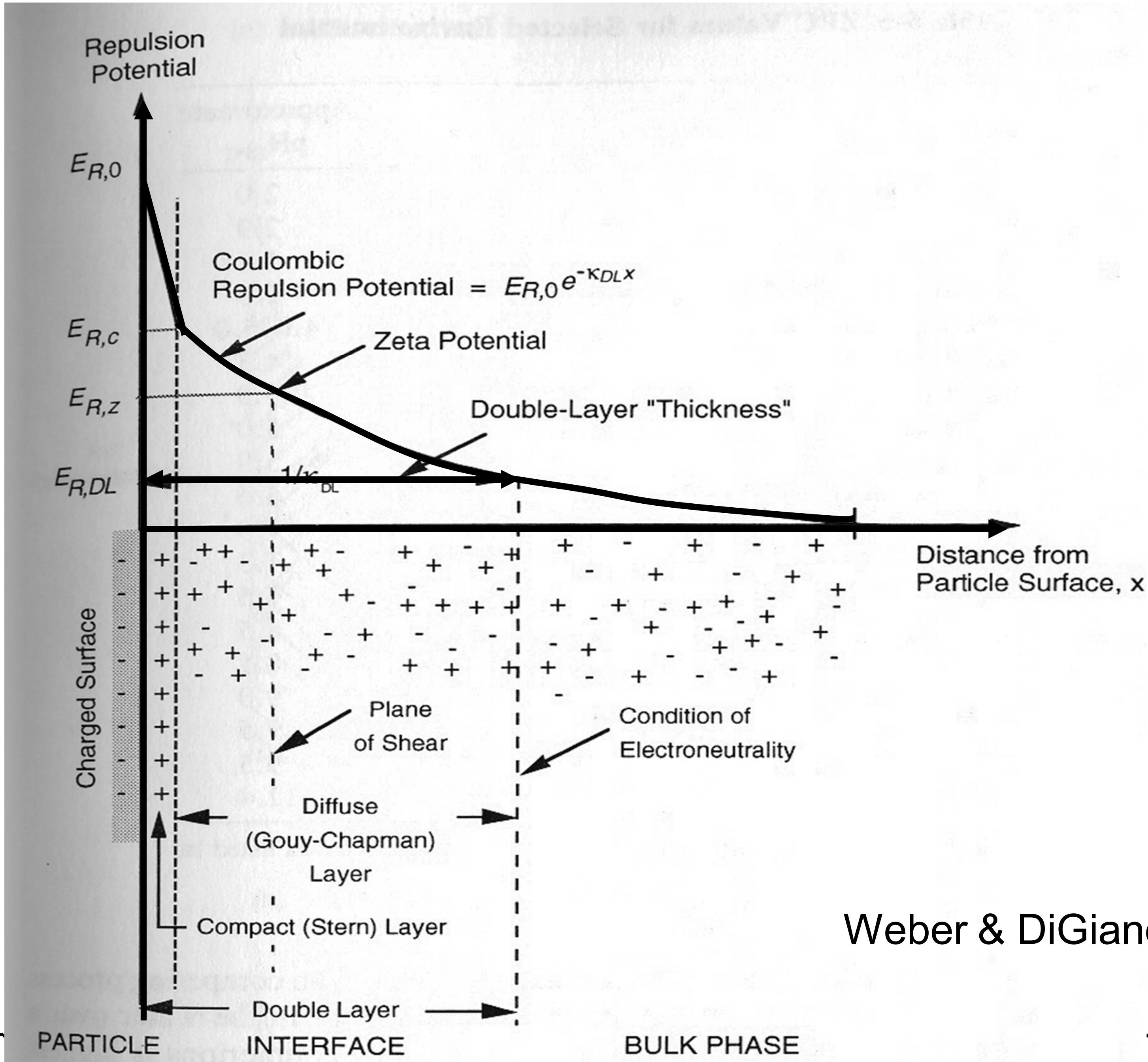


Primary charge on particles

Development of electric double layer
With higher concentration of counterions
close to the particle in solution

Weber & DiGiano, 1996

Double Layer Representation

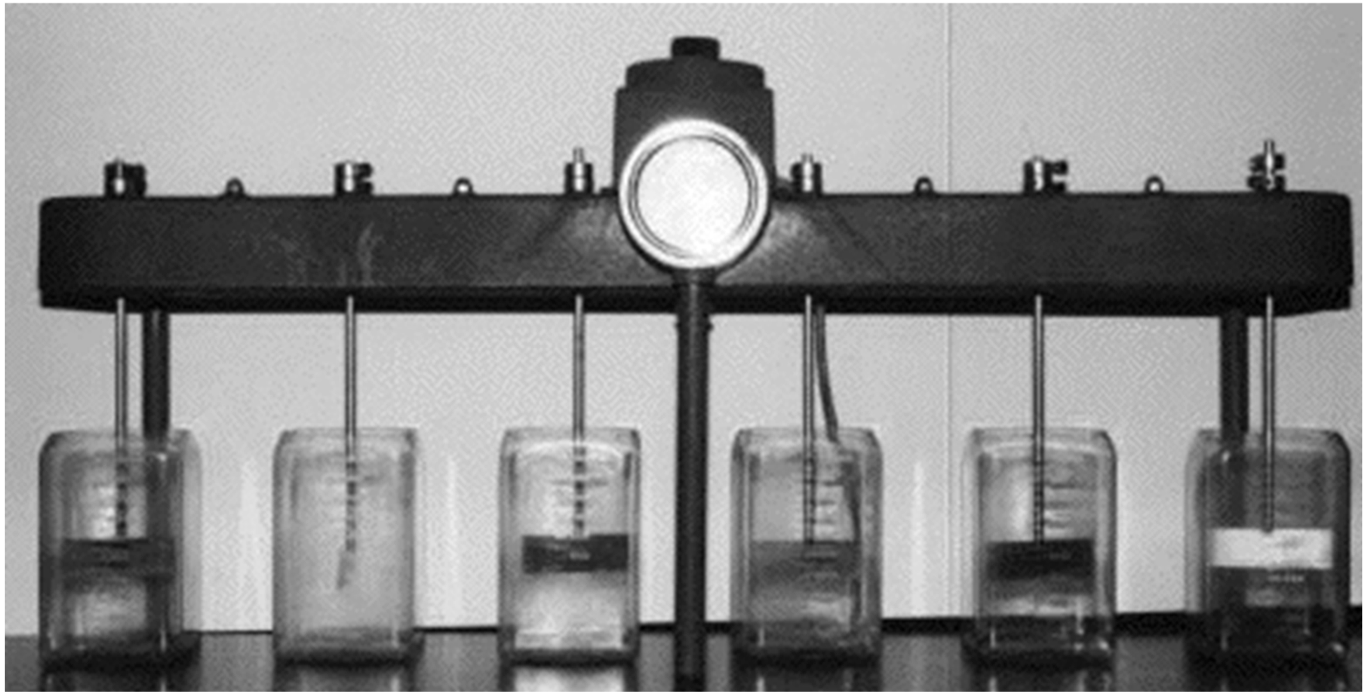


Weber & DiGiano, 1996

Coagulants & Mechanisms of Coagulation

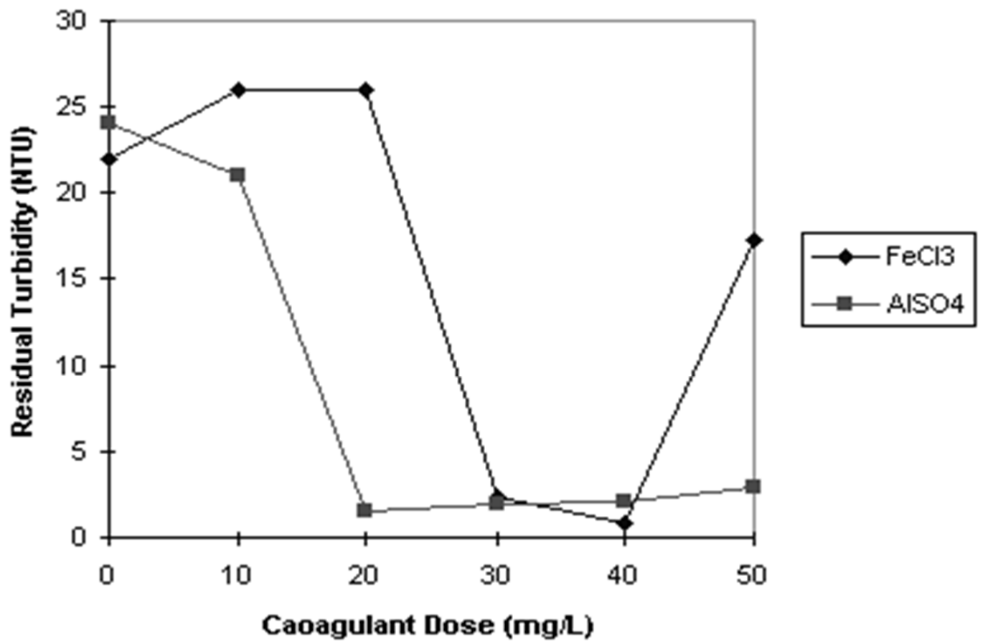
- Examples of Coagulants
  - Alum ($Al_2(SO_4)_3$), Ferric chloride, Ferrous sulphate, polyelectrolytes
  - Polyelectrolytes can also be added as coagulant aids
- Mechanisms of Coagulation
  - Double Layer Compression by indifferent electrolyte
  - Adsorption and Charge Neutralization by potential determining electrolyte
  - Enmeshment in a precipitate
  - Adsorption and interparticle bridging by polymers-nonionic / anionic / cationic
- A coagulant such as alum can act by more than one mechanism
  - The dominant mechanism is affected by pH, alkalinity and colloid concentration

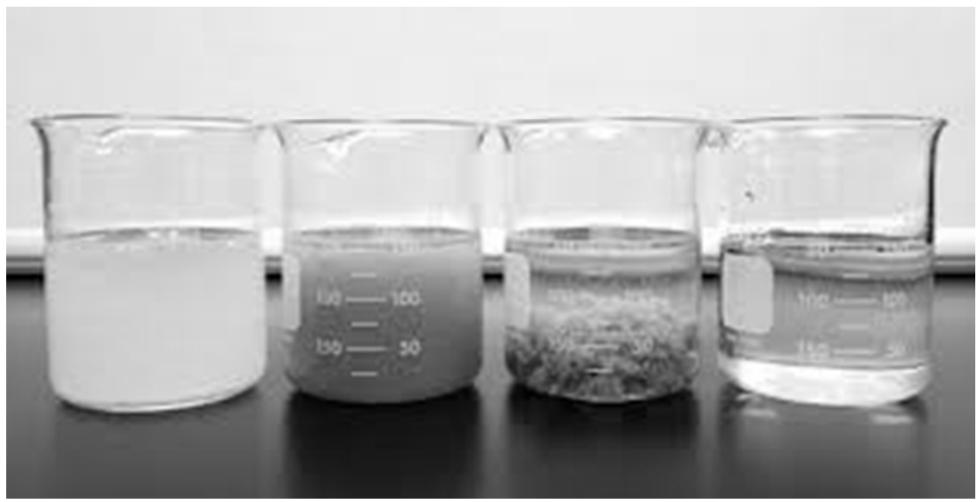
Jar Test Apparatus
Coagulation-Flocculation and Settling



- ✓ Six Containers➔ For testing various coagulant dose + 1 Control
- ✓ Variable mixing speed, same for all containers
- ✓ 100 rpm 1 min; 25-35 rpm 20-30 min; no mixing 1 h

Jar Test: Turbidity Vs Coagulant Dose

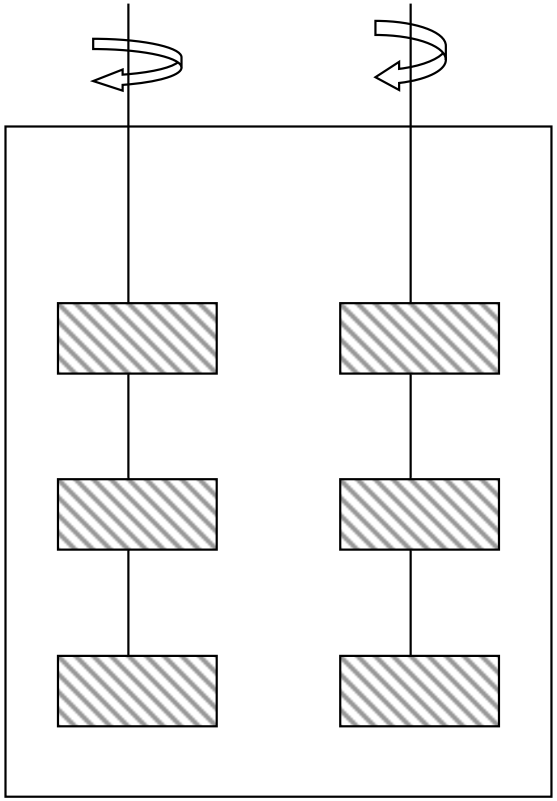




Flocculation

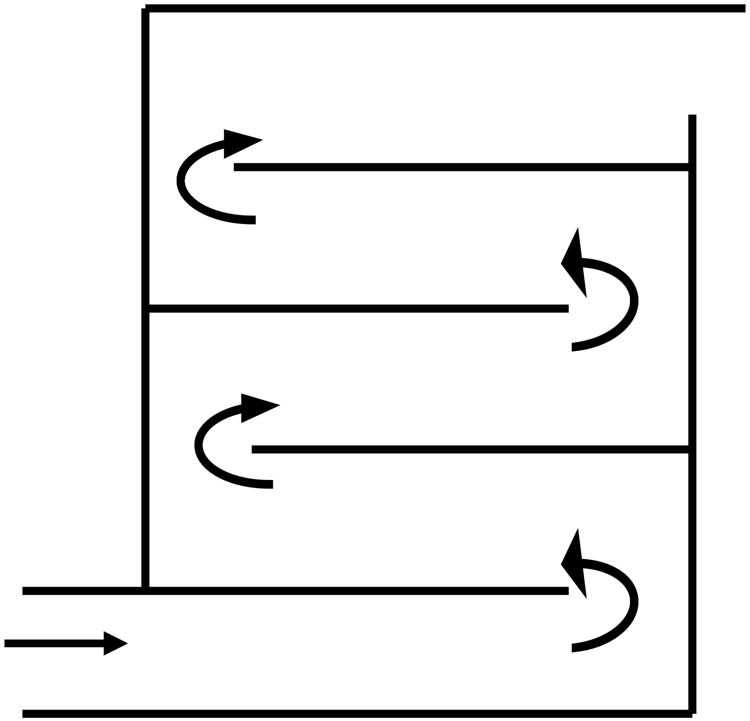
- The rate of aggregation of destabilized colloidal particles; depends on:
  - Rate at which collision occurs between particles
  - Effectiveness of these collisions in causing attachment
- Mechanisms of interparticle contact
  - Contacts by thermal motion (Brownian motion), bulk fluid motion (Induced by stirring), & particle settling
- Two types of flocculation processes
  - Perikinetic flocculation → Intrinsic property controlled by Brownian motion
  - Orthokinetic flocculation → Affected by mean velocity gradients ($\overline{G}$) characterizing spatial changes in velocity; relates to power input for mixing
  - Typical $\overline{G}$ value for flocculation: 10-100 s^{-1} and retention time in flocculation basin 20-60 min; Gt value determines the mass of flocs formed

Flocculation



Paddle Flocculator

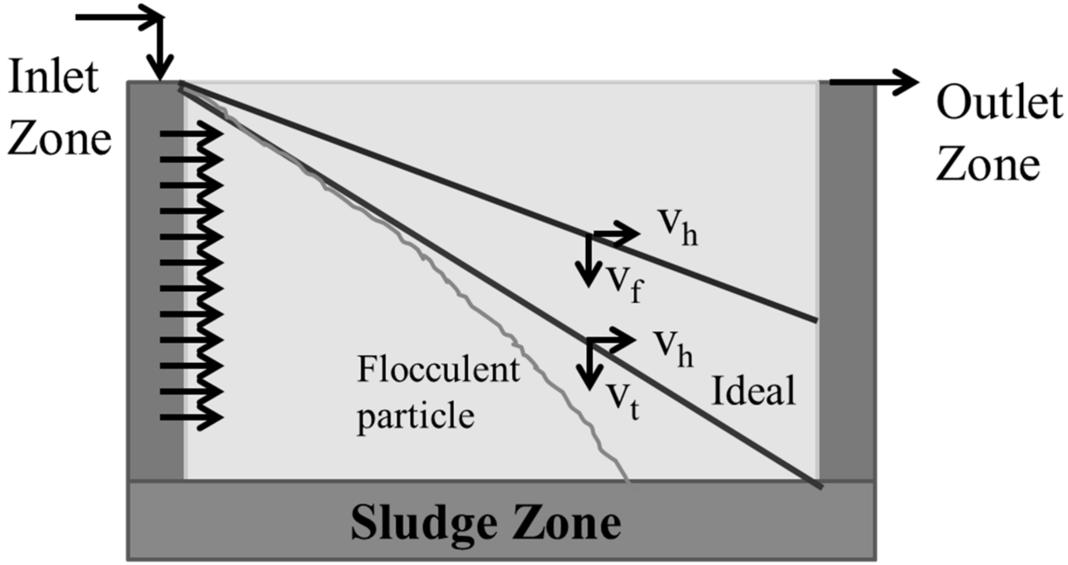
✓ Gentle agitation promotes contact between destabilized particles



Baffled Flocculator

✓ Long flow path promotes contact between destabilized particles

Discrete Particle Settling



The treated water is skimmed from the surface; the sludge containing the settled solids is collected at the bottom in sludge hoppers

$$t_D = \frac{V}{Q} = \frac{L.W.D}{Q} = \frac{D}{v_t}$$

$$v_t = \frac{Q}{L.W} = \frac{Q}{A_s} = \text{Overflow rate}$$

- ✓ Particles that completely settle are determined not by depth (D) but by the tank surface area (A_s)
- ✓ For discrete particle $v_t=f(d_p)$ is the terminal settling velocity given by Stokes law

t_D is the detention time; v_t is the terminal settling velocity

Class 2 Settling: Settling of Flocculant particles

- ✓ Settling of discrete particles occurs as per class 1 settling behavior; Settling of flocculant particles is class 2 settling
- ✓ Particles coalesce / flocculate during sedimentation, hence the mass increases and the particles settle faster
- ✓ Settling efficiency is determined through sedimentation tests in settling column
- ✓ Extent of flocculation is a function of contact opportunities, overflow rate, depth, velocity gradients, particle conc. and particle size range

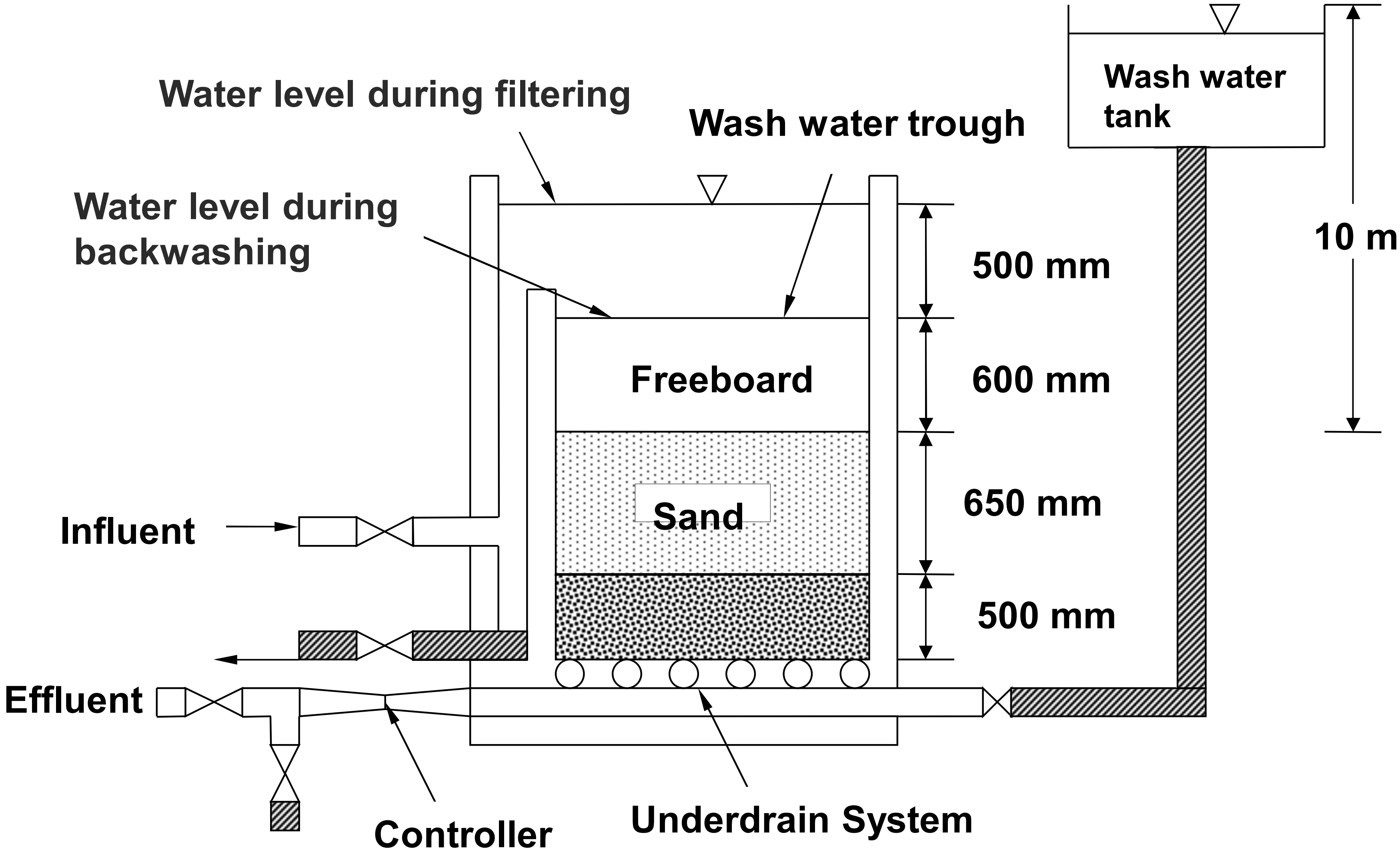
Rapid Sand Filtration

- Removes the flocs that resist settling; they can hinder disinfection
- Consists of a bed of sand packed in a deep bed above a layer of gravel
- The removal of particulate materials by accumulation throughout the depth of a filter medium as water passes through it. NTU at effluent ~0.5 NTU
- **Primary Mechanism: Physicochemical filtration**

  particle removal by physical and chemical forces between the particles (p) and the media/collector (c) – transport and attachment of particulates ($d_c/d_p \approx 1000$)

  Little decrease in permeability compared to cake filtration/straining filtration

Rapid Sand Filter



Typical Effective size of sand > 0.45 mm; Uniformity Coefficient < 1.5

Rapid Sand Filtration

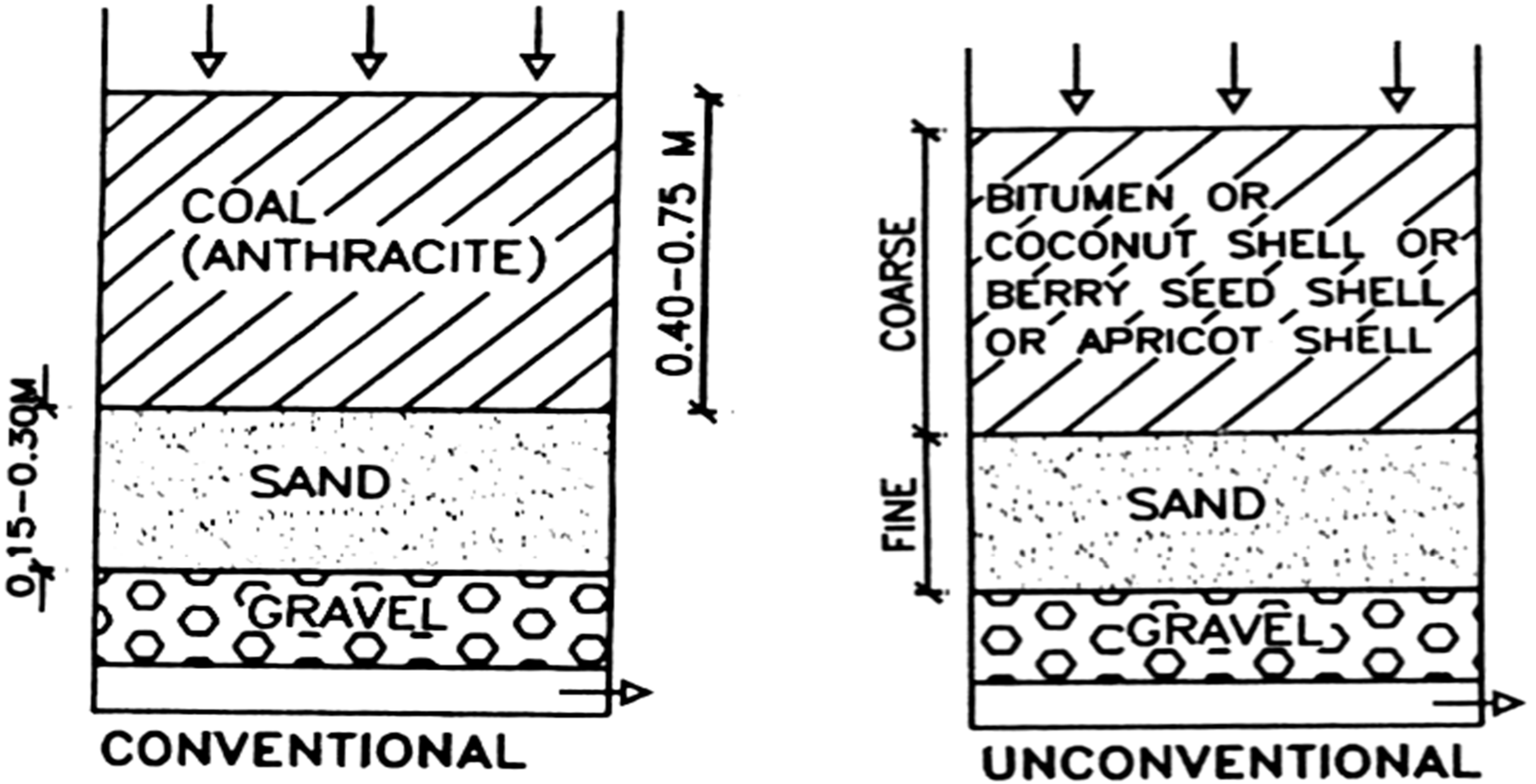
- Filter media: bed of sand grains called collectors of a suitable size range
  - Effective size d_{10} :size of grains in mm such that 10% of particles by weight are smaller
  - Uniformity coefficient $C_u = d_{60}/d_{10}$
- Consists of 0.45-0.76 m of sand supported by 0.45 m of gravel. d_{10} range 0.45-0.7 mm. C_u range 1.2-1.75
- Flow rate range 1- 4 gpm/sq ft (2.4-34 m/h)
- Can be operated as gravity filters or pressure filters
- Cleaned by backwashing

Backwashing

- With time, deposits build up, decreasing porosity and permeability of filter media
- Head loss increases, flow rate decreases at a constant hydraulic head
- Shear stress on deposited particles increases and water quality decreases
- Backwashing involves flow reversal through the bed. Hydraulic shear dislodges particles. Also includes surface scour
- Typical flow rates 36-48 m/h. Time of backwashing 3-15 min after a 12 hr run. Volume of backwash water 2-5% of filtered water. Accompanied by bed expansion of 20-50%
- For media particles with similar specific gravity, backwashing causes fine to coarse grading of the filter media with increasing depth

Dual Media/ Multi-Media Filters

- A special type of rapid sand filter, i.e., collectors of different material and specific gravity
- Coarse grains of a lighter material can lie above finer grains of a heavier material.



Slow Sand Filters

- Finer sand grains (0.2 mm) of greater (0.9-1.5m) depth; lower filtration rate 0.1-0.3 m/h
- Produces good water quality but requires large land area
- Solids removal in upper zone “Schmutzdecke” accompanied by some biological activity. Cleaning by scrapping the top 1” at 1-6 months interval.

Disinfection Using Chlorine

- Scope: To destroy the pathogens
- Common Disinfectants:
  - Cl_2 gas (most widely used)
  - Calcium hypochlorite $Ca(OCl)_2$
  - Sodium hypochlorite $Na(OCl)_2$
  - Ozone
  - UV Radiation

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

$$HOCl \leftrightarrow H^+ + OCl^-$$

- Residual Chlorine → Chlorine available for disinfection
- Free available residual chlorine → $[HOCl] + [OCl^-]$

Disinfection Using Chlorine

- **Chlorine demand**
  - Exerted by organic and inorganic substances in reduced form that are oxidized by chlorine
  - eg. Inorganic compounds : Fe^{+2}, Mn^{+2}, NO_2^-, H_2S
  - eg. Organic compounds: Ammonia, Organic matter.
- **Reactions of NH_3 with Chlorine**
  - NH_3 often present in wastewater
  - Mono, di and tri chloramines are formed
  - Chloramines have germicidal action but they are slow acting

$$NH_3 + HOCl \rightarrow NH_2Cl + H_2O$$

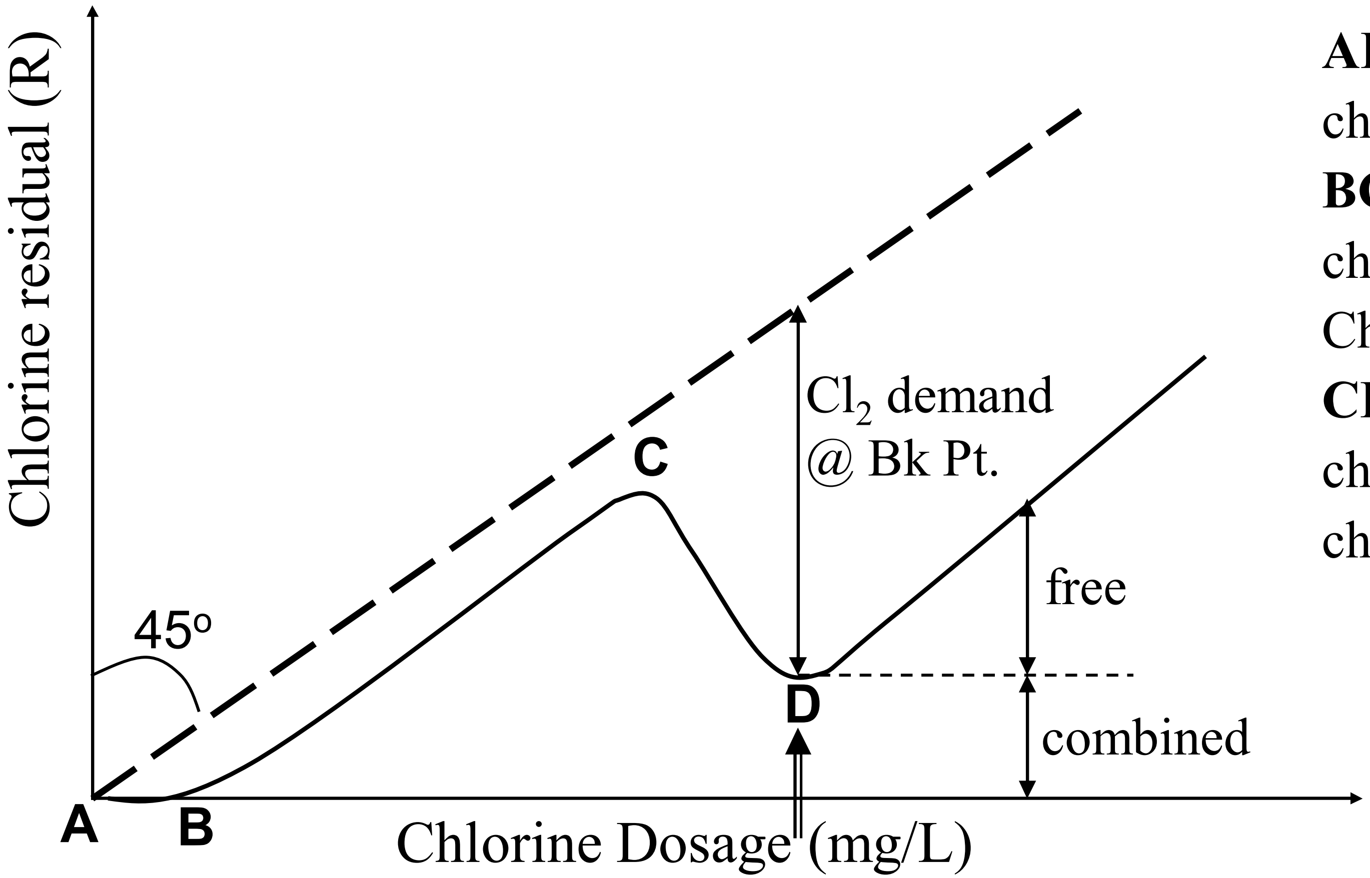
$$NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O$$

$$NHCl_2 + HOCl \rightarrow NCl_3 + H_2O$$

$[NH_2Cl]$ & $[NHCl_2]$ = f (pH, temperature, Contact time, HOCl)

Disinfection Using Chlorine

- **Combined Residual Chlorine**
  - Chlorine residual in combination with NH_3 and organic nitrogen compounds



AB – Destruction of chlorine by reduced substances
BC – formation of chloramines & Choloroorganic compounds
CD - Destruction of chloramines & choloroorganic compunds

$NH_2Cl \rightarrow N_2, N_2O$
$Cl_2 \rightarrow Cl^-$

Disinfection Using Chlorine

- **Breakpoint Chlorination:**
  - Variation of residual chlorine in water with increasing Cl_2 dose for water and wastewater containing ammonia and other organic nitrogen compounds
  - Cl_2 dosage beyond breakpoint will cause a proportional increase in free available chlorine
  - Depending on water quality, chlorine dose up to 10 mg/L may be needed to obtain chlorine residual of 0.5 mg/L
- **For good chlorination use Cl_2 dose > Cl_2 at breakpoint**

Bacterial/Germicidal action of Cl_2

- Oxidize the bacterial cell's chemical structure thereby destroying enzymatic process
- Protozoan cysts & enterovirus are more resistant to Cl_2
- Rate of disinfection = f (conc. & form of available residual chlorine, pH, Temperature, contact time)
  - **HOCl → Hypochlorous acid is 40-80% most effective – can kill virus**
  - **OCl^- → Hypochlorite ions are less effective**
- Chloramines → disinfecting power lower than OCl^- , more persistent
- Some combined residual is desirable (although less effective)
  - Protect DW recontamination in distribution system
  - Controls algal & bacterial after-growth in treated waters
- Problem of Cl_2: Conversion of organic matter to carcinogenic Trihalomethanes (THMs)

Disinfection

- Disinfection of water containing natural organic matter (NOM) with chlorine may cause generation of disinfection by-products (DBPs) such as trihalomethanes (THMs)
- Apart from the disinfection process other processes also causes removal of pathogens, such as protozoan cysts
  - Coagulation-Flocculation & Settling
  - Filtration
  - Softening with Lime Soda process (at high pH)
- Removal of turbidity and NOM is essential for achieving good disinfection