Chapter 6: Solid-Liquid Separation in WWTPs

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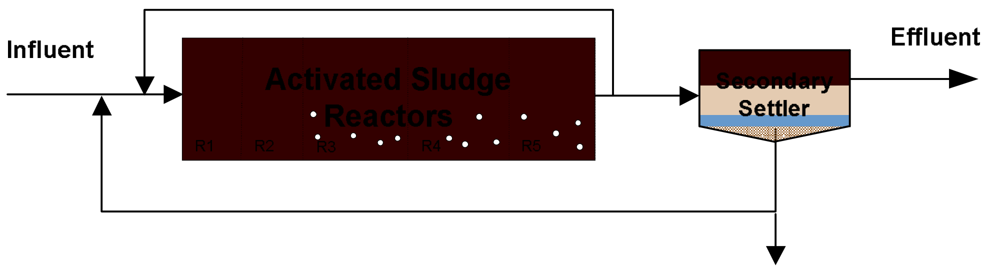
Introduction to Solid-Liquid Separation

Introduction: Separation Methods

Solid/liquid separation technologies → Ensure good effluent quality & biomass retention in the biological reactors.

- **<u>Filtration</u>** units
- **<u>Flotation</u>** units
- **<u>Settlers</u>** <u>(based on gravity sedimentation)</u>

  - Most extended method in water lines of WWTPs with activated sludge processes

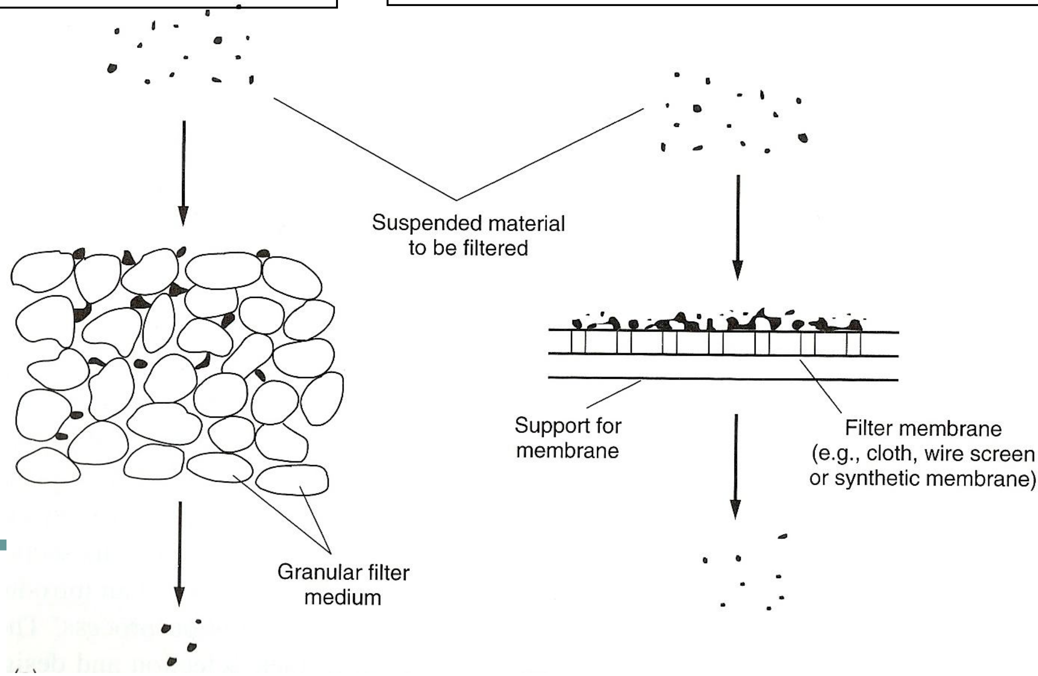


  - Their optimum design and operation are crucial for a correct WWT process performance

Introduction:Filtration

Filtration

- Depth Filtration
  - Removal of TSS occurs within and on the surface of the filter bed
- Surface Filtration
- Membrane Filtration
  - (Surface Filtration and Membrane Filtration) Removal of TSS occurs on the surface of a straining surface or a thin supported membrane



Introduction: Filtration

Depth Filtration

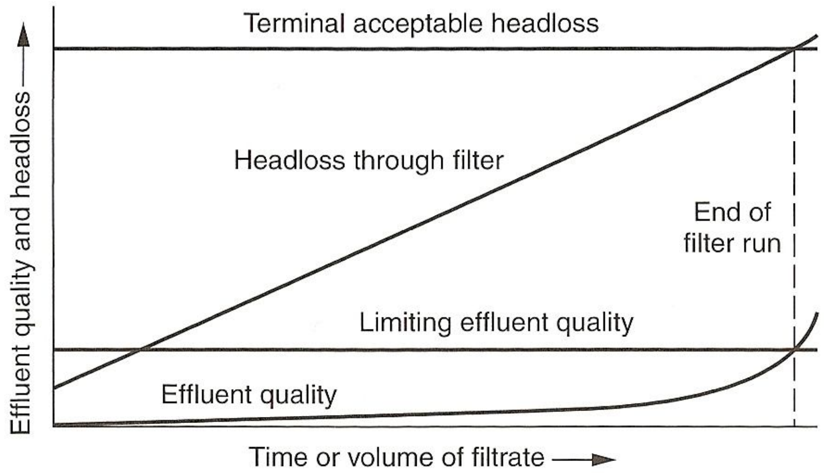
- Supplemental removal of TSS in WWTP effluent
- Pretreatment for membrane filtration

High rate filters operate at 80–200 L $m^{-2}min^{-1}$

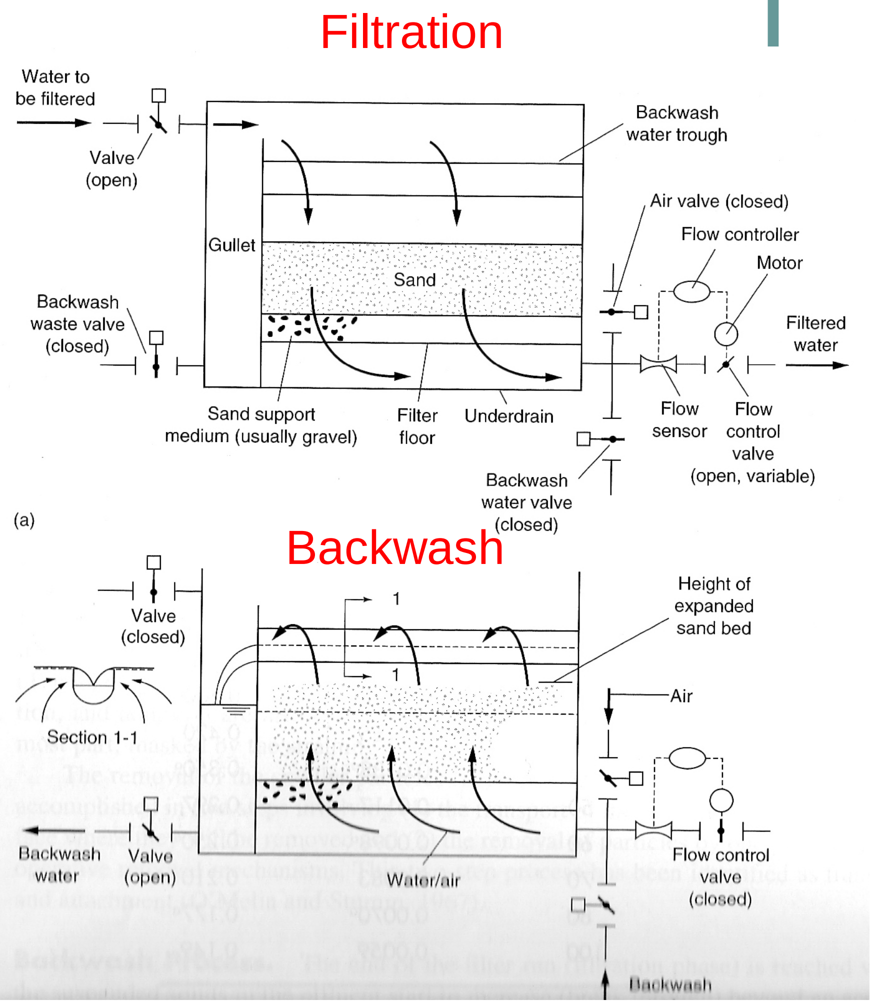
Medium particle size 0.7-2 mm

Materials: Anthracite & Sand

Height: 30-210 cm



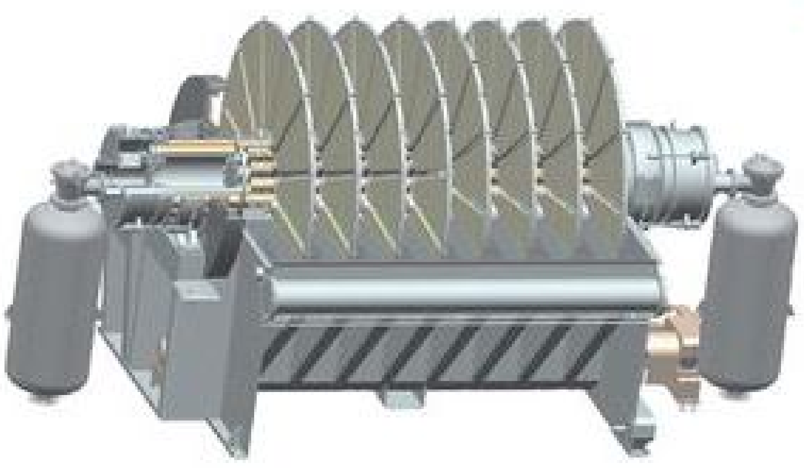
Time course of TSS in the effluent and Head Loss

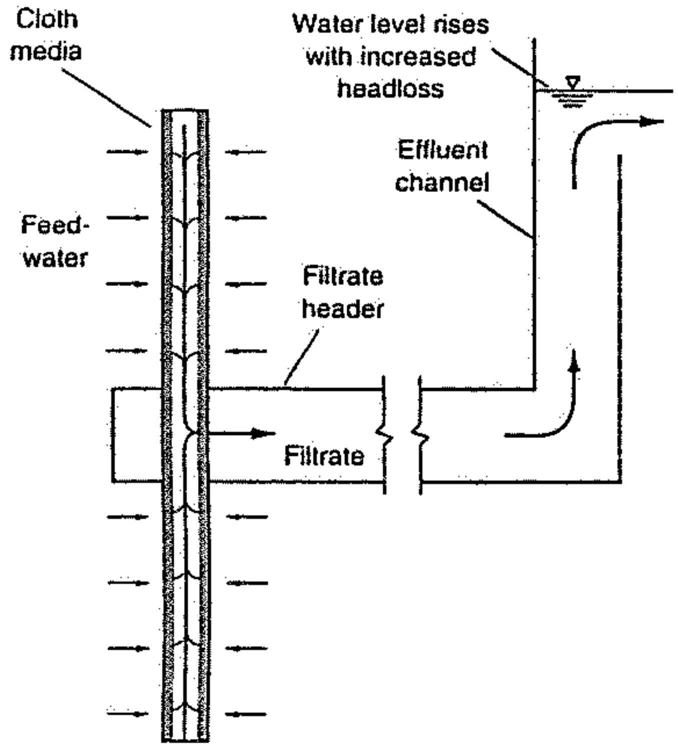


Introduction: Filtration

Surface Filtration

- Removal of residual TSS suspended solid from secondary effluents
- Pore size ranging from 20 to 35 μm
- Materials: Woven metal fabric or cloth fabric
- Operation at 0.25 – 0.83 $m^3\ m^{-2}\ min^{-1}$
- Head loss 75- 150 mm



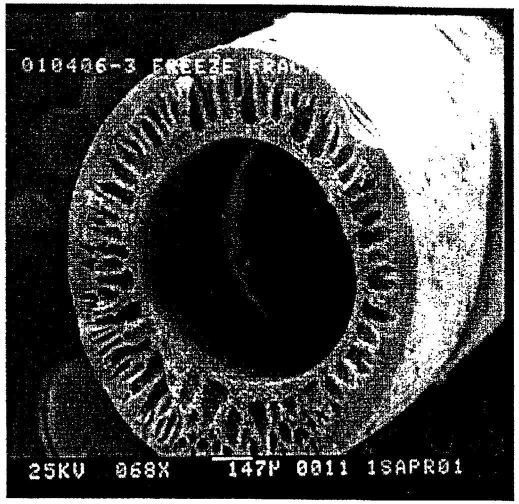


(a)

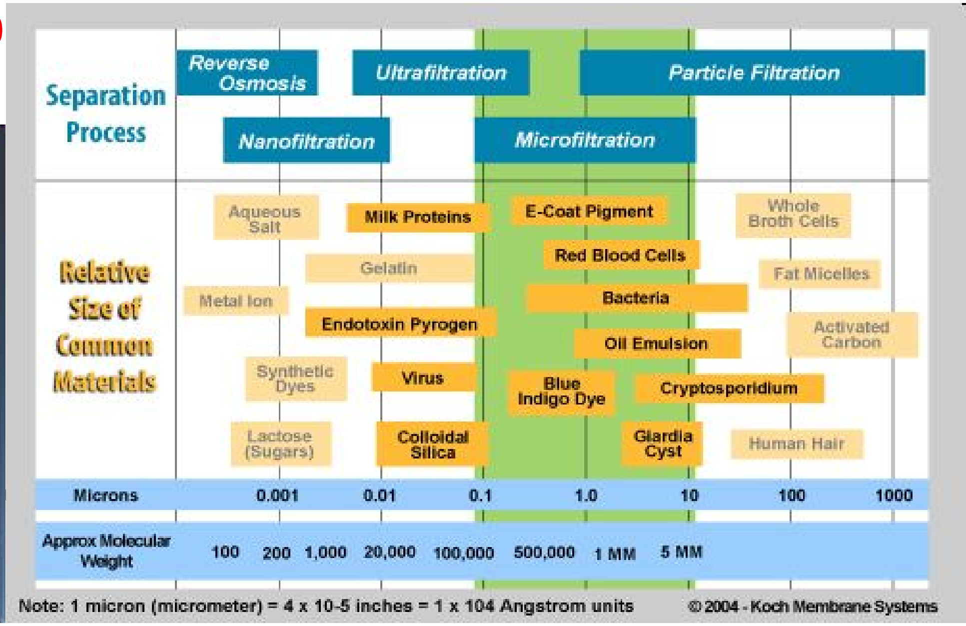
Introduction: Filtration

Membrane Filtration

- Removal of TSS and colloidal matter
- Pore size ranging from 0.0001 to 1 μm
- Materials: polyamide, cellulose acetate, polypropyilene
- Operation at 0.0003 – 0.0011 $m^3\ m^{-2}\ d^{-1}$ for Microfiltration
- Head loss (operating pressure) 1 m → 0.4 kWh m^{-3}

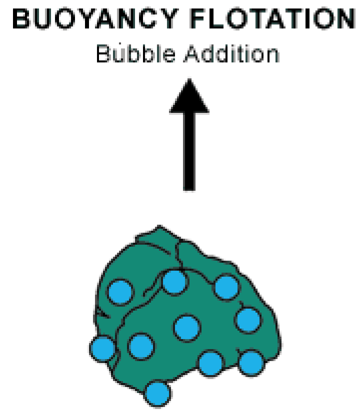


Compact configuration → 50 – 80 % footprint savings



Introduction: Flotation

<ins>Flotation:</ins> Introduction of fine air bubbles into the liquid phase. These bubbles attach to the TSS floc and cause the floc to rise to the surface.



Employed for the removal of TSS and concentration of biosolids

Ideal for small or light particles

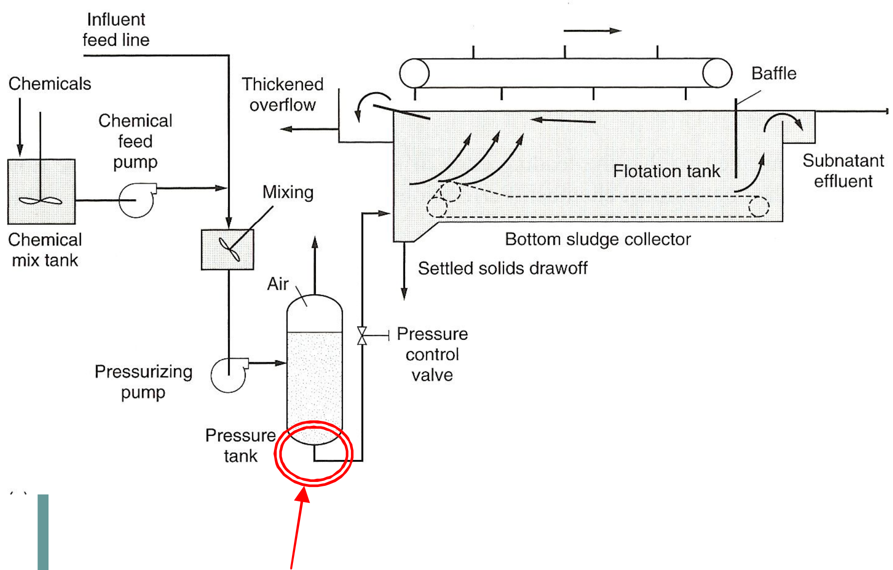
Two types:

- <ins>Dissolved Air Flotation</ins>: Air injected in pressurized wastewater (most common)
- <ins>Dispersed air Flotation</ins>: Air injected at atmospheric pressure

Addition of chemicals to aid flotation: Enhanced air bubble adsorption Aluminum or Ferric salts, activated silica

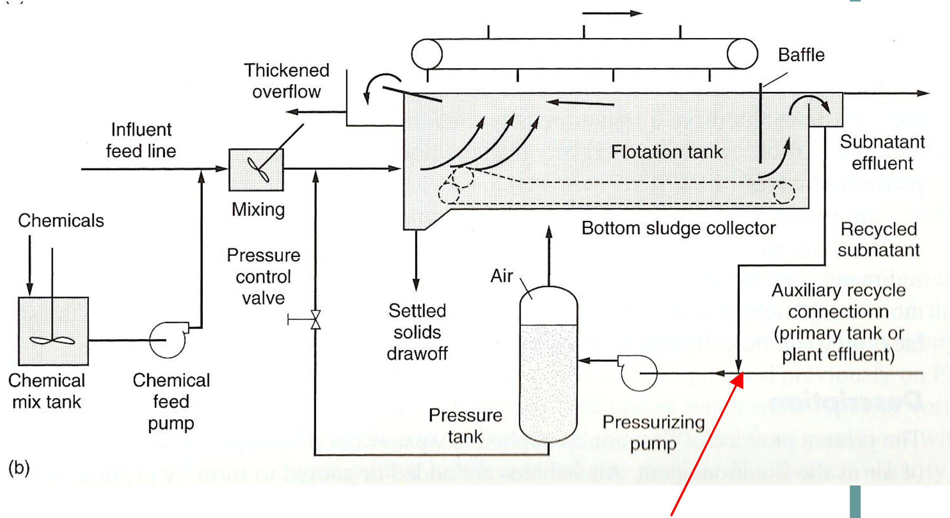
Introduction: Flotation

Small DAF systems



2,7-3.5 bar

Large DAF systems



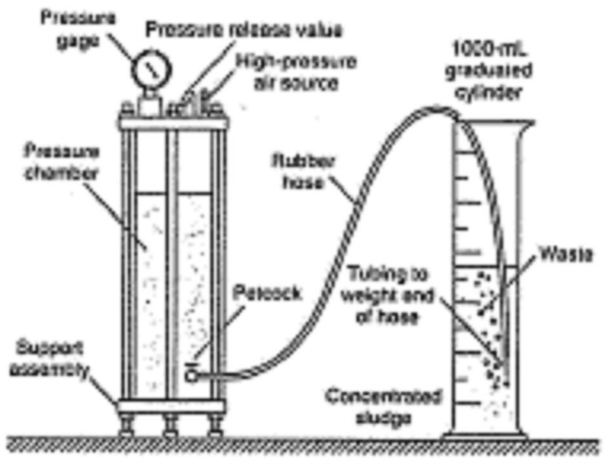
15 – 120 % of the influent

Typical loading rates in Air Flotation systems: 1.2-3 kg m^{-2} h^{-1} for mixed liquor or 2.4 to 4 kg m^{-2} d^{-1} for settled sludge. Comparable to gravity settlers 4-6 kg m^{-2} h^{-1}.

Introduction: Flotation

Design parameter (A/S – Volume of air/Mass of Sludge). Experimentally determined. Typically 0.005-0.06 ml mg^{-1}.

$$\frac{A}{S} = \frac{1.3 \times s_a \times (f \times P - 1)}{S_a}$$



where: *A/S* is the air to solid ratio, ml air mg TSS^{-1}

s_a = air solubility in water

f = Fraction of air saturation, typically 0.5

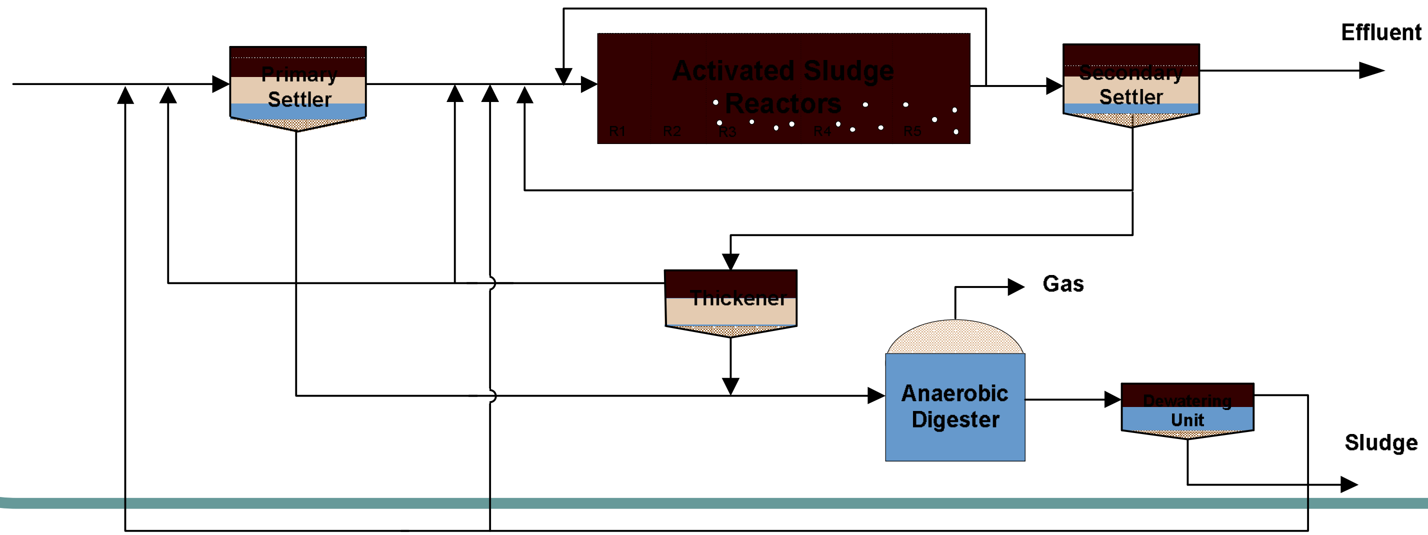
P = pressure, atm = (p + 101.35)/101.35, with gage pressure in kPa

S_a = Influent suspended solid concentration (mg l^{-1})

Introduction: Sedimentation

<u>Sedimentation:</u> separation of suspended particles heavier than water by gravitational settling.

- Primary settlers: Before activated sludge units for suspended solids removal and grit removal
- Secondary settlers: After activated sludge units to separate the treated wastewater from the biological sludge mass
- Thickener & Dewatering units: In the sludge line for water removal and TSS concentration



Introduction: Sedimentation

Grit removal units: Sand, gravel and cinder (solid materials much heavier than water.

Located after screening units and before primary sedimentation tanks

Devised to:

- Protect equipments from abrasion
- Reduce formation of heavy deposits in pipelines, and channels
- Reduce the frequency of digester cleaning due to excessive accumulation of grit

Three types:

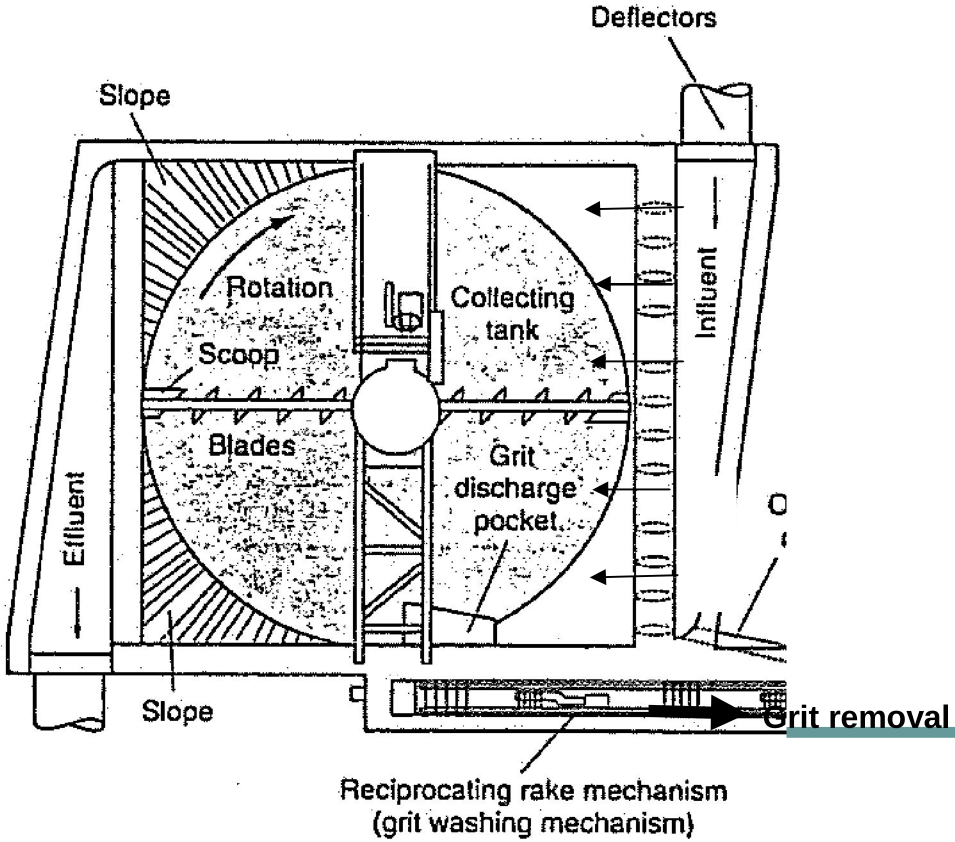
- Horizontal Flow Chamber: Wastewater flow in a horizontal direction
- Aerated chamber: Aeration creates a spiral-flow-enhanced sedimentation
- Vortex chamber: centrifugal and gravitational forces separate the grit

Introduction: Sedimentation

Two Types: Square and Rectangular horizontal flow grit chamber (less used)

Designed to remove heavy particles in the range of 0.15-0.21 mm

Square Horizontal Flow Grit Chamber



Typical Design Parameters

Detention Time: 60 s

Horizontal velocity: 0.3 m/s

Length allowance for inlet and outlet turbulence (25-50 %)

Introduction: Sedimentation

<u>Aerated Chamber:</u> Removes particles larger than 0.21 mm

Figure 5-33

Typical section through an aerated grit chamber.

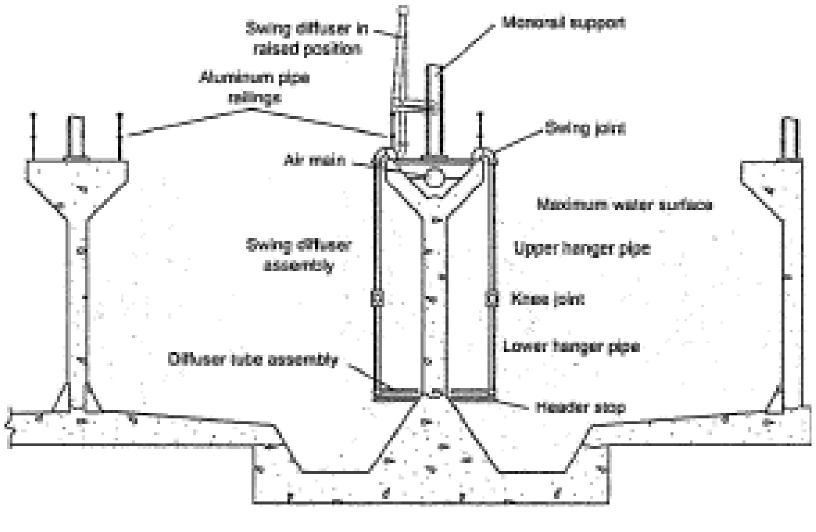
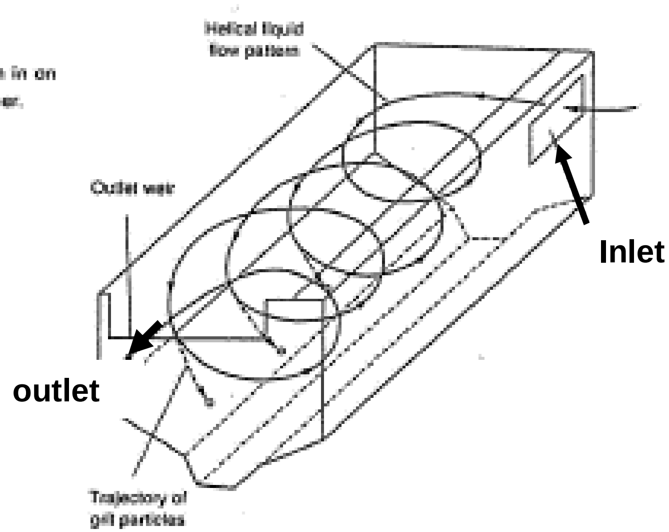


Figure 5-34

Helical flow pattern in an aerated grit chamber.



<u>Typical Design parameters</u>

Detention time 3 min

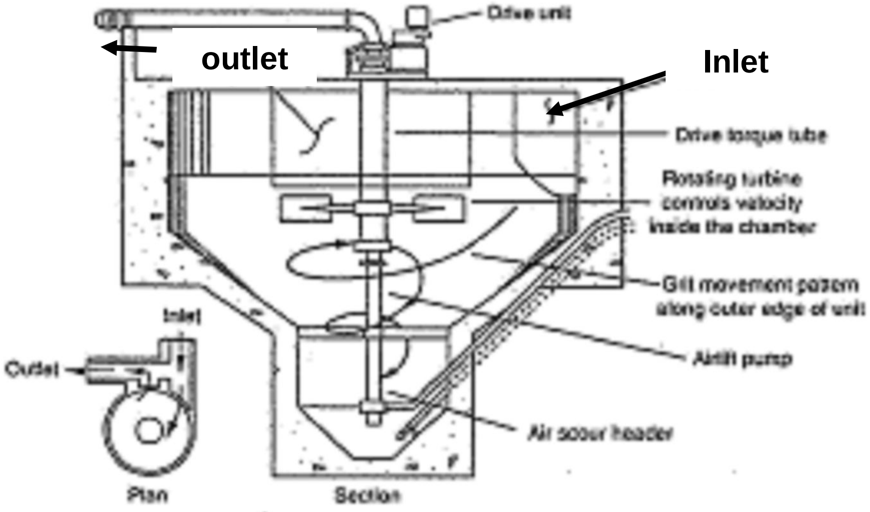
Width:Depth ratio 1.5:1

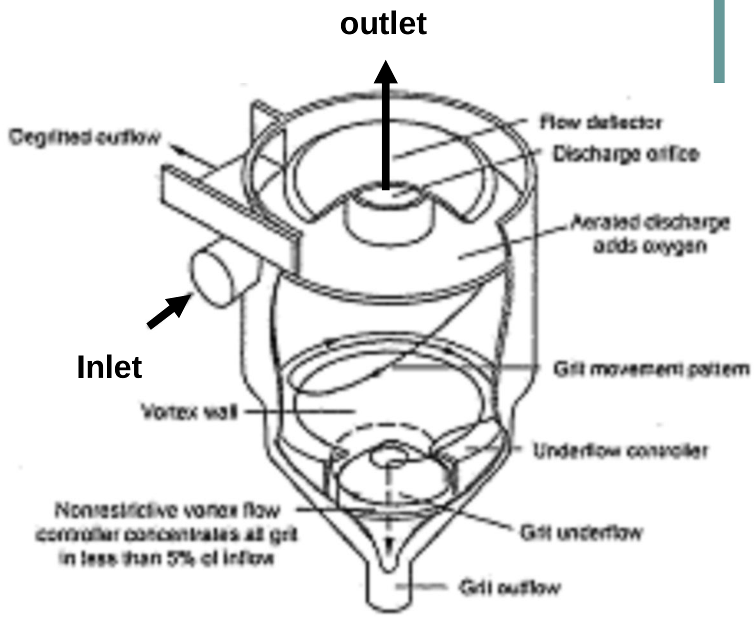
Length: width ratio 4:1

Introduction: Sedimentation

Vortex-Type Grit Chamber: Removes particles larger than 0.21 mm

Removal Efficiencies > 95 % for particles larger than 0.3 mm





Typical Design parameters

Detention time 30 S

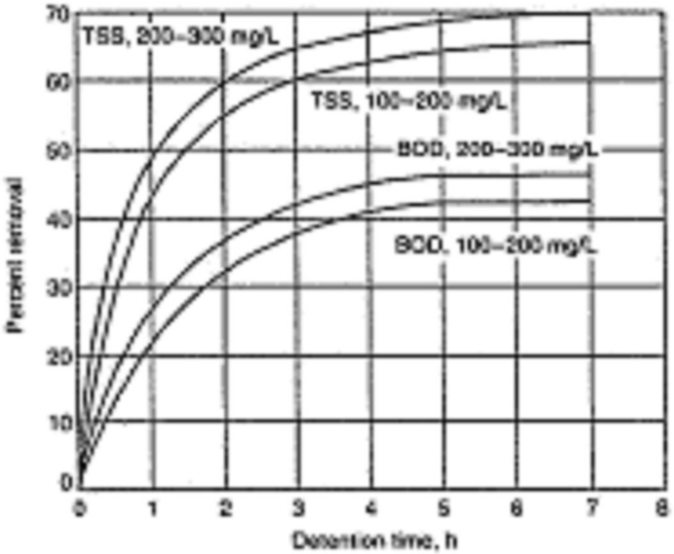
Introduction: Sedimentation

Primary Sedimentation: Removes easily settleable solids and floating material

Efficiently designed and operated primary settlers remove 50-70 %TSS and 25-40 % BOD

Figure 5-46

Typical BOD and TSS removal in primary sedimentation tanks. (Greeley, 1938.)



$$BOD - RE\ (\%) = \frac{\text{Retention Time}}{0.018 + 0.02(\text{Detention Time})}$$

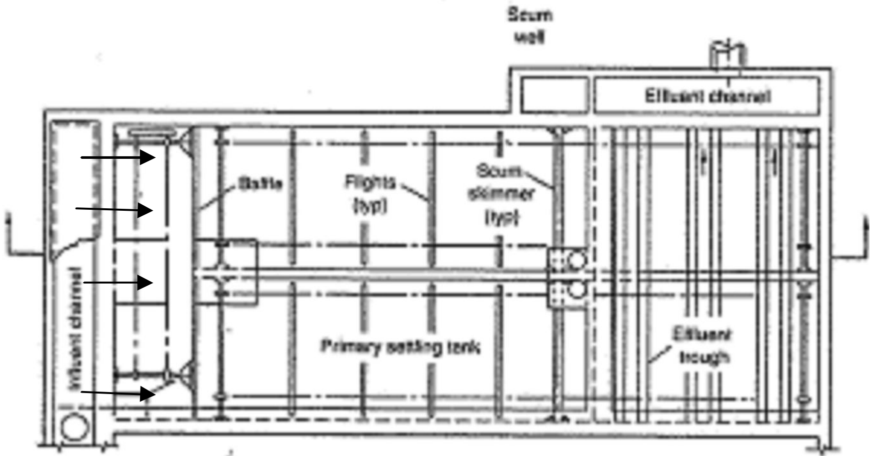
$$TSS - RE\ (\%) = \frac{\text{Retention Time}}{0.0075 + 0.014(\text{Detention Time})}$$

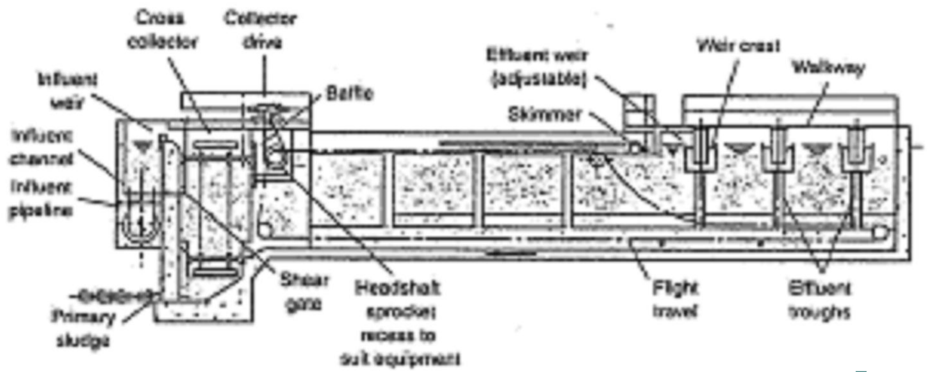
Two main types:

- Rectangular
- Circular

Introduction: Sedimentation

<u>Rectangular primary sedimentation tanks</u>: Solids Removal via chain and flight solids collector or travelling-bridge-type collector





<u>Typical Design parameters</u>

Detention Time: 2 h

Average overflow rate 40 m^3/m^2d

Depth: 3- 4.9 m (4 m)

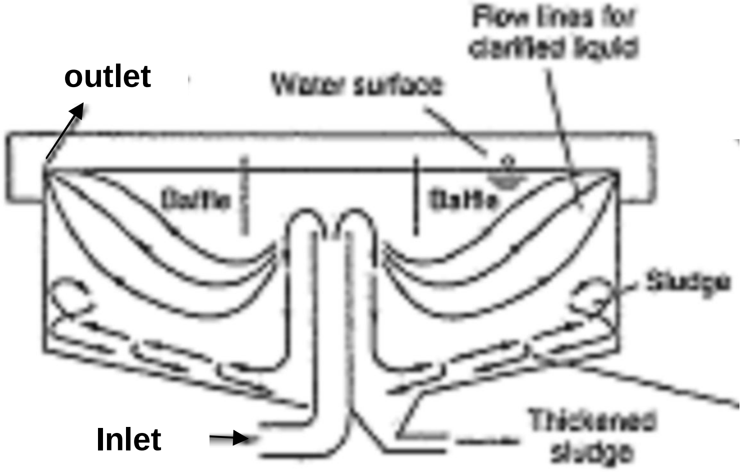
Length: 24-40 m

Width: 0.6-1.2 m

Multiple Rectangular Tanks require less area than Multiple Circular Tanks

Introduction: Sedimentation

Circular primary sedimentation tank:



Typical Design parameters

Detention Time: 2 h

Average overflow rate 40 m^3/m^2d

Depth: 3- 4.9 m (4 m)

Diameter: 12-45 m

Slope: 1/12 m/m

Fight speed 0.03 rpm

Introduction: Sedimentation

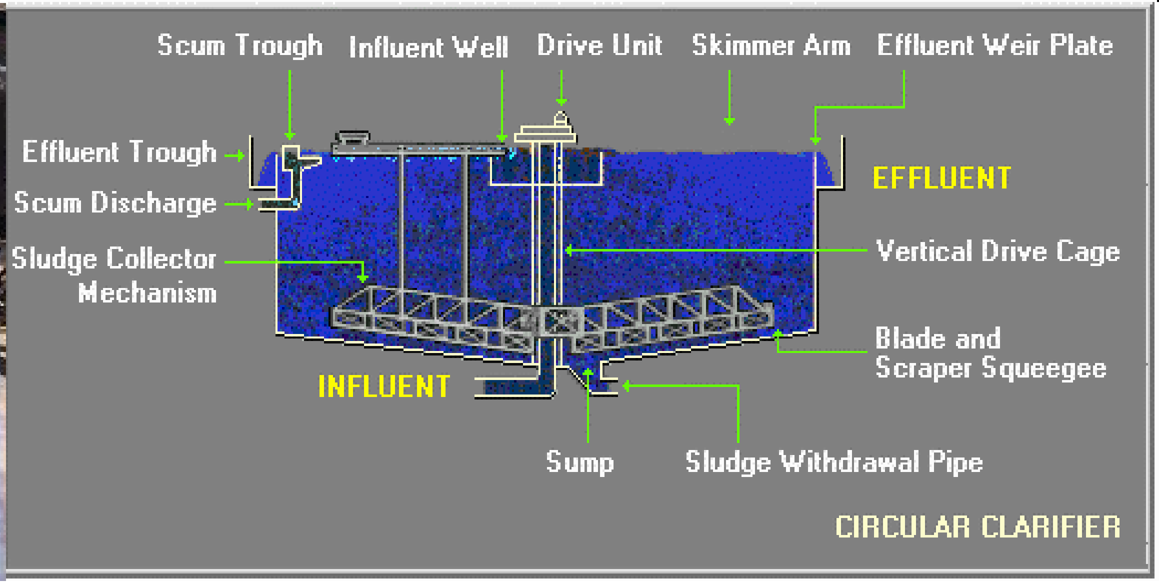
Secondary Sedimentation Tanks: Similar to primary tanks but the special nature of the large flocculent solids induce special considerations

Circular or rectangular configurations

Overflow rates based on peak flow conditions: 40-64 m^3/m^2d

Solid Loadings: 8 kg/m^2 d (peak conditions)

Depth 3.5 – 6 m



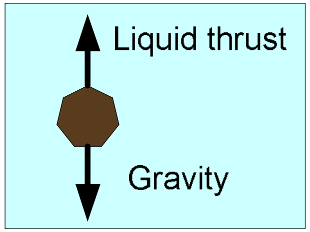
Fundamentals of settling processes

Fundamentals of the Solid-Liquid separation process

Settling

- Separation of particles from liquid by gravity

  In wastewater, two forces are acting over a floc: Liquid thrust and gravity → when gravity forces are stronger (particles with higher density than water), particles have descendent velocity



- Suspended particle settling is influenced by :
  - Type of suspended particle

    Particle origin, shape, concentration, temperature…
  - Tendency of the particles to flocculate

    Particles tend to aggregate in structures called flocs

Typical Secondary Settler

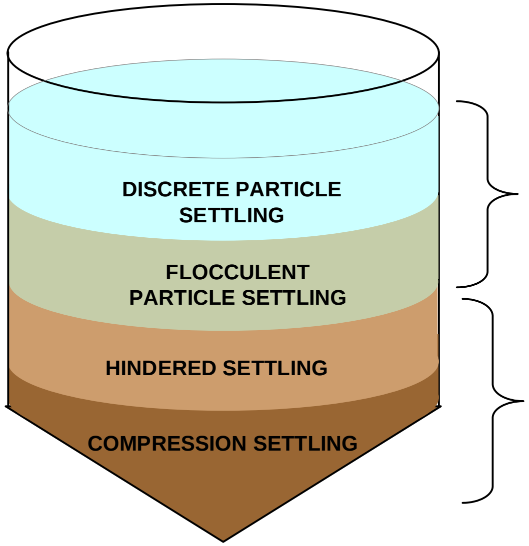
Fundamentals of the Solid-Liquid separation process

Four types of settling patterns depending on the nature and concentration of the particles

1. Discrete particle settling:
   - Solids that settle as individual entities with little or no interaction with other particles
2. Flocculent particle settling:
   - Flocculation of solid particles as they settle through the water column
3. Hindered settling:
   - Inter-particle forces are significant. A mass of particles settling as a unit
4. Compression settling:
   - Settling is achieved by compression caused by the weight of particles added to the sludge blanket

Fundamentals of the Solid-Liquid separation process

Clarification and Thickening



CLARIFICATION:
Settling process for discrete or flocculent particles

THICKENING:
Settling process for particles existing as a unit of mass

Settling velocity (v_s)

- Depends on the settling characteristics
- Important parameter for design and operation of the settlers

Introduction: Design of Secondary settlers

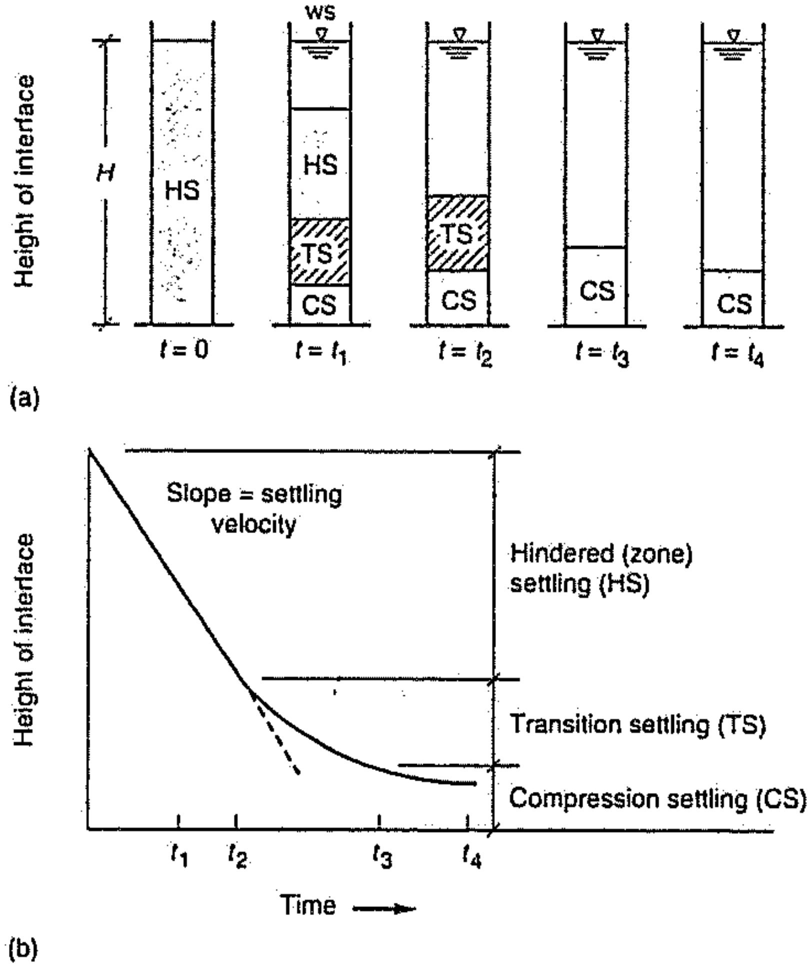
At high TSS concentration (2500-3500 mg/L) the sludge settles as a blanket, the particles maintaining the same relative position with respect to each other → **Hindered settling**

The Design Overflow rate Q/A depends on

- Area needed for Thickening
- Area needed for Clarification
- Rate of sludge withdrawal

Two methods to design settlers:

- Talmadge & Fitch (Data from one or more batch tests)
- Solid Flux Method (Data from settling tests at different TSS concentrations)



Introduction: Design of Secondary Settlers

Method of Talmadge & Fitch:

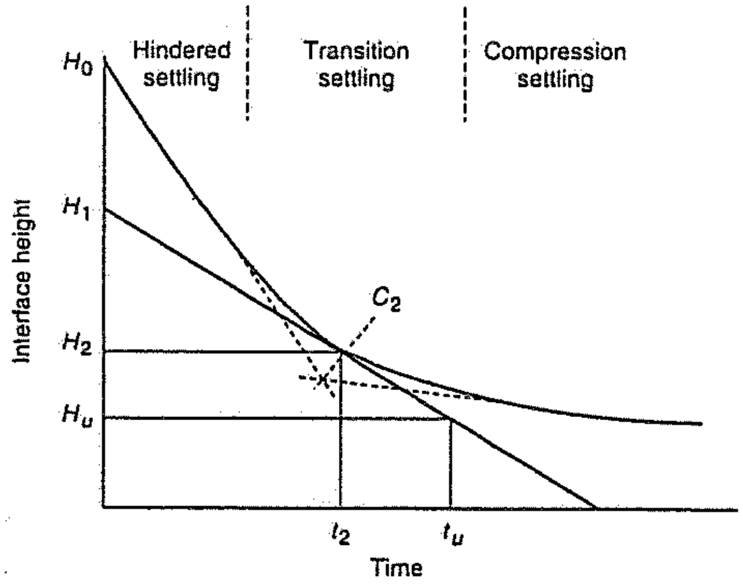
Area required for thickening is usually larger that the area required for clarification

$A_{thickening} = \frac{Q \cdot t_u}{H_o}$ where Q is the flow rate into the tank (m^3/s);

H_o (m) is the initial height of the column test; t_u (s) time to reach the desired underflow concentration (C_u)

The critical concentration determining the solid handling capability of the settler is C_2, which is determined by the intercept of the tangents to the hindered and compression regions

t_u is then determined as the intercept of the tangent to the settling curve in C_2 and H_u, where $H_u = \frac{C_o H_o}{C_u}$, with C_u and C_o the underflow and initial TSS concentrations



The position of the sludge blanket-clarified liquid interphase is recorded periodically

Introduction: Design of Secondary Settlers

<u>Solid Flux Analysis Method:</u> The area of the settler depends on the limiting solids flux that can be transported to the bottom of the sedimentation basin.

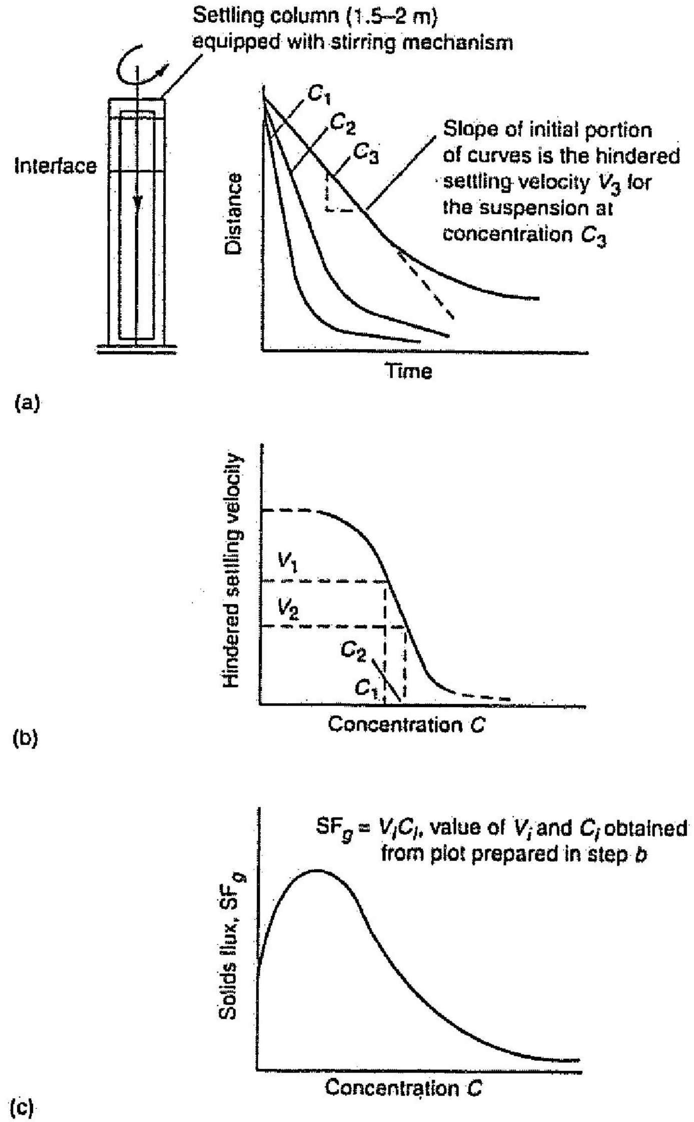
Data derived from settling tests at different sludge concentrations is needed.

$$\text{Total Mass Flux of Solids } (SF_t) \text{ at any point} =$$

$$\text{Gravity Mass Flux} + \text{Underflow Mass Flux} =$$

$$C_i \cdot V_i + C_i \cdot U_b = C_i \cdot V_i + C_i \cdot \frac{Q_u}{A}$$

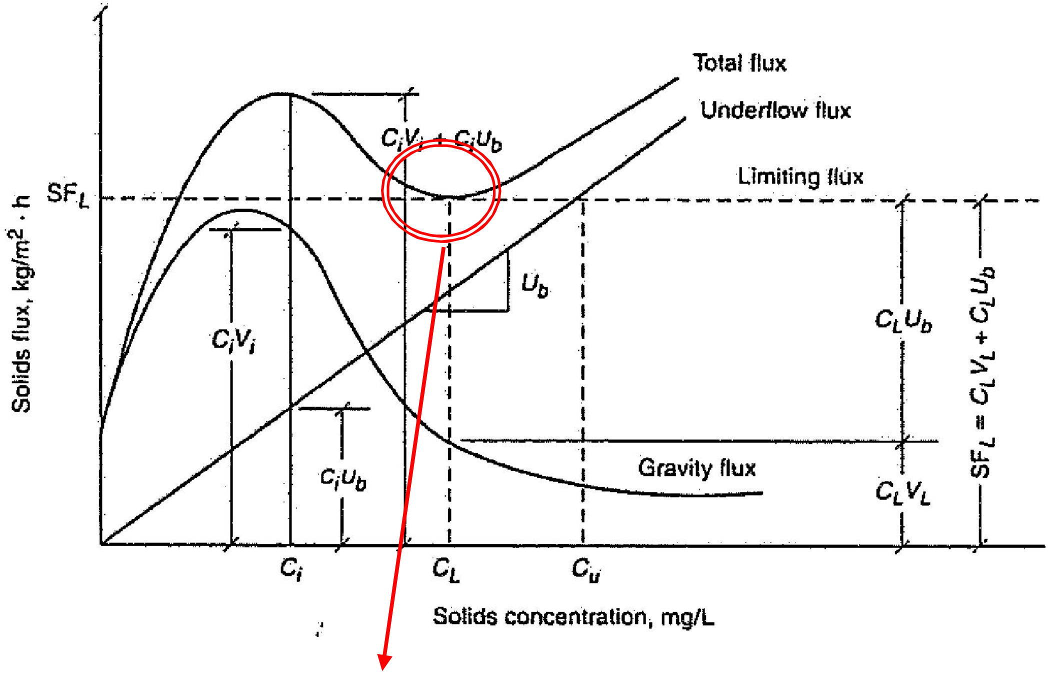
C_i TSS at any point; V_i settling velocity of the solids by gravity; U_b bulk downwards velocity



Introduction: Design of Secondary Settlers

$$A = \frac{(Q + Q_u) \cdot C_o}{SF_L}$$

$$C_u = \frac{SL_F}{U_b}$$



This is limiting Solids Flux
that can be processed in the settler

Fundamentals of the Solid-Liquid separation process

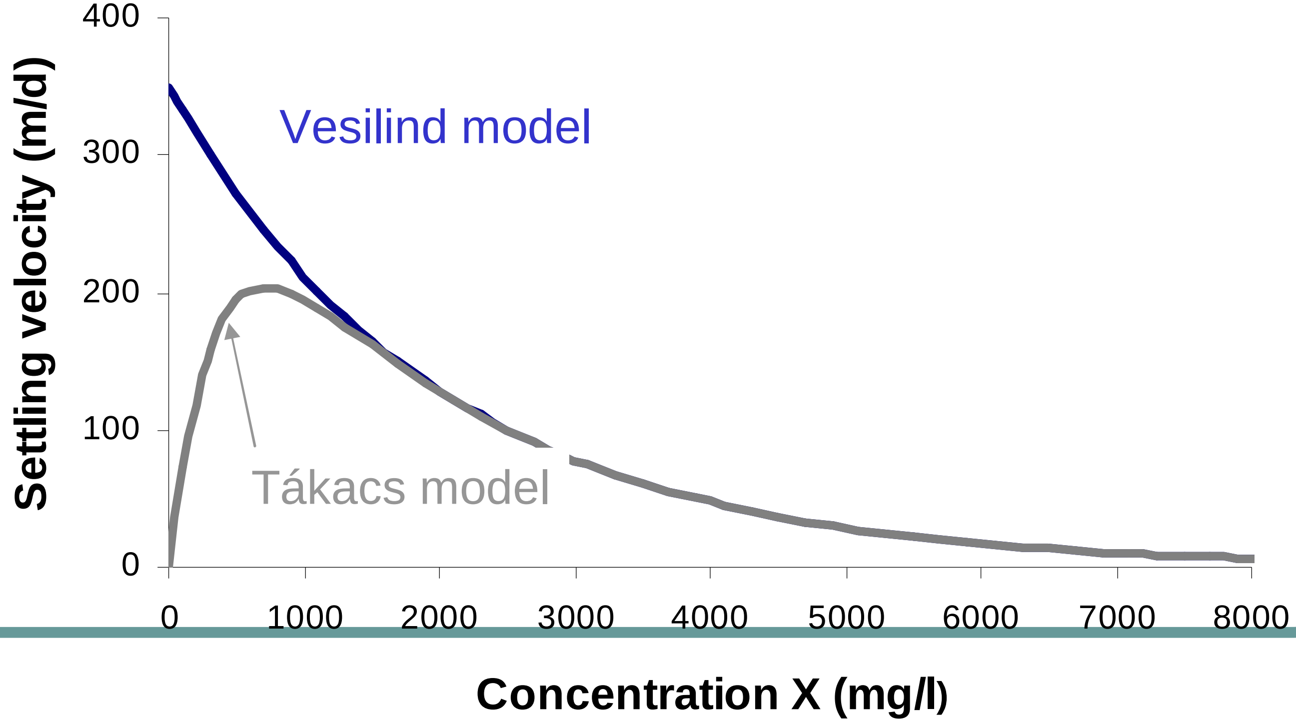
Settling velocity (v_s)

- Vesilind Model (1968): Thickening effect

$$v_s = v_0 \cdot e^{-\alpha X}$$

- Tákacs model (1991): Thickening + clarifying effects

$$v_s = v_0 \cdot (e^{-\alpha X} - e^{-\beta X})$$



Settling modelling

Settler Models

Stationary models

- Simplified models
- The settler is considered as an splitter
  - The physical dimensions and configuration of the settler is not considered
- Based on steady-state mass balances

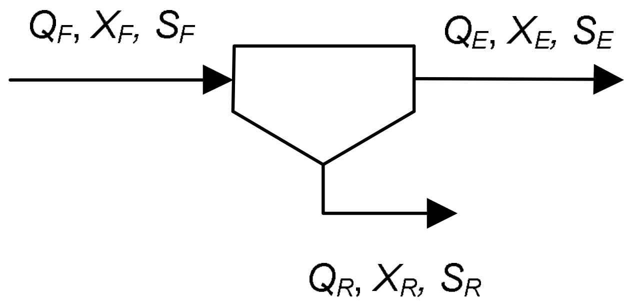
Dynamic models

- Distribution of solids (particulate components) in the settler
- 1-D, 2-D, 3-D models
- Biological reactions inside the settler can be considered

Simplified Settler Models

Stationary models (I)

- Model components are gathered into soluble and particulate components (TSS)
- Soluble component concentrations are equal in the recycle and effluent
- Particulate component removal is determined by f_{NSS} (Fraction of X_F that is non-settleable)



$$Q_F = Q_E + Q_R$$

$$Q_F \cdot S_F = Q_E \cdot S_E + Q_R \cdot S_R$$

$$Q_F \cdot X_F = Q_E \cdot X_E + Q_R \cdot X_R$$

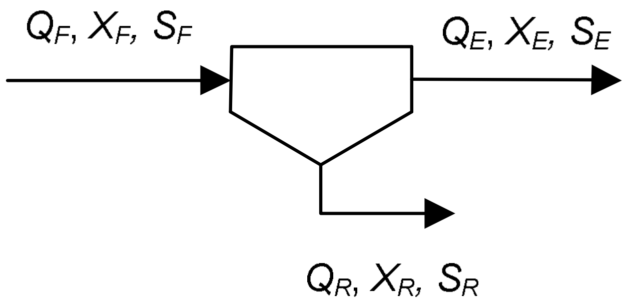
$$S_F = S_E = S_R$$

$$X_E = f_{NSS} \cdot X_F$$

Simplified Settler Models

Stationary models (II)

- Model components are gathered into soluble and particulate components
- Soluble component concentrations are equal in the recycle and effluent
- Solid removal can be also calculated by an efficiency parameter (η) that indicates the mass flux eliminated in the settler



$$Q_F = Q_E + Q_R$$

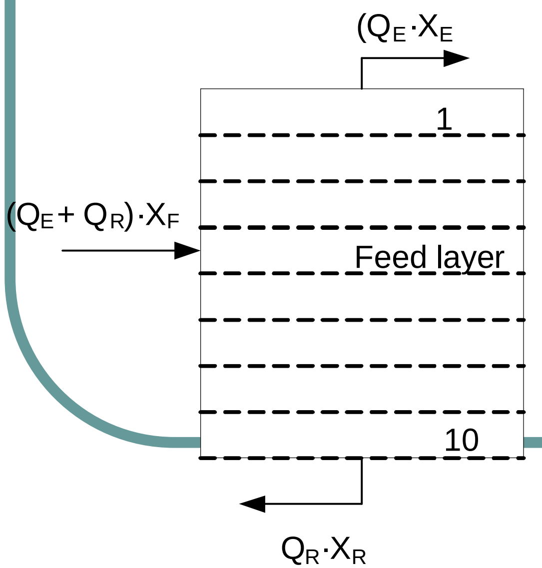
$$Q_F \cdot S_F = Q_E \cdot S_E + Q_R \cdot S_R \qquad S_F = S_E = S_R$$

$$Q_F \cdot X_F = Q_E \cdot X_E + Q_R \cdot X_R \qquad X_R = \eta / 100 \cdot \frac{Q_F \cdot X_F}{Q_R}$$

Dynamic Settling Models

1-D models

- Predict the concentration of solids in one dimension (along the settler height)
- Horizontal gradients of solids are negligible and horizontal velocities are uniform
- For their numerical resolution, ***layer models*** are the most common solution
- Tracy and Keinath (1973), Laikari (1989), Tákacs (1991)…



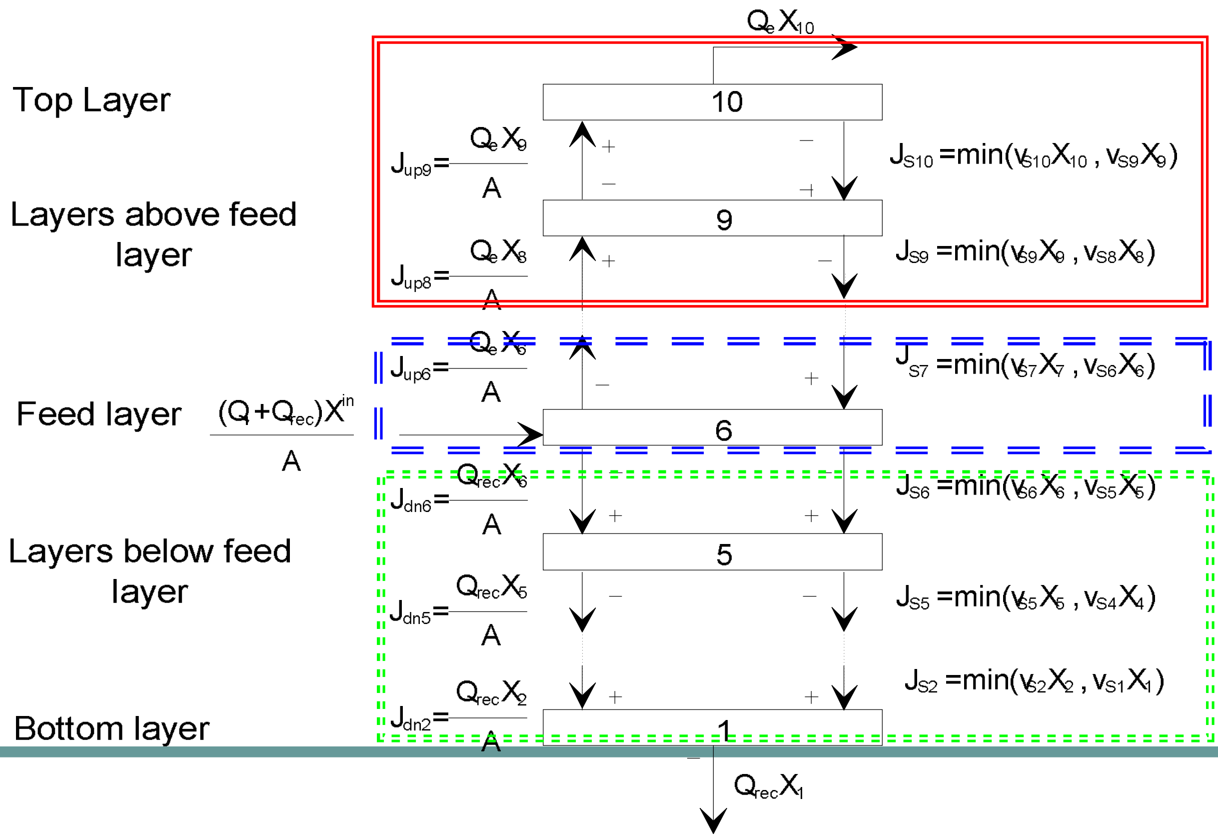
$$\frac{dV_i X}{dt} = FX_{in} - FX_{out}$$

- The settler is divided into a number of horizontal layers (min 5)
- Each layer has a *complete stirred reactor* behaviour
- Mass flux balance is applied in each layer

Dynamic settling models

Tákacs model (1991)

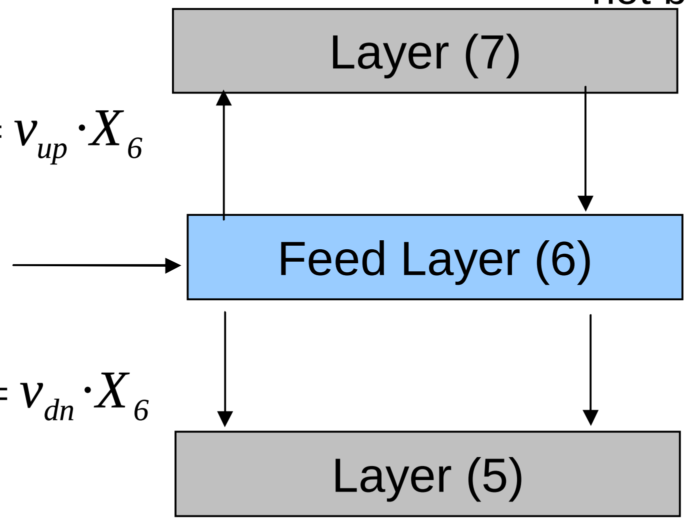
1. Layers model based on the flux theory
   - Solids entering the settler are governed by a gravity settling flux (J_S) and a bulk flux caused by the underflow rate (J_{DN}) and overflow rate (J_{UP})



Layers model (Tákacs *et al.*, 1991)

Mass fluxes in ***Feed layer***

Gravity flux out of a layer can not be greater than the gravity flux of the layers above



$$J_{up,6} = v_{up} \cdot X_6$$

$$J_f = \frac{Q_f \cdot X_f}{A}$$

$$J_{dn,6} = v_{dn} \cdot X_6$$

$$J_{S,7} = \min\left(v_{S,7} \cdot X_7, v_{S,8} \cdot X_8\right)$$

$$J_{S,6} = \min\left(v_{S,6} \cdot X_6, v_{S,7} \cdot X_7\right)$$

$$v_{up} = \frac{Q_{ef}}{A}$$

$$v_{dn} = \frac{Q_{rec}}{A}$$

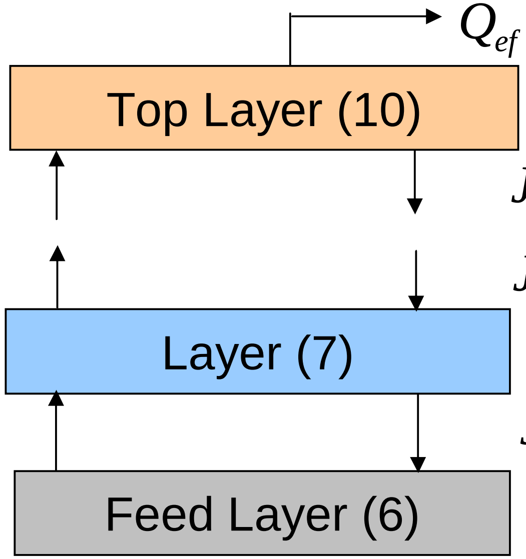
$$\frac{dX_6}{dt} = \frac{\frac{Q_f X_f}{A} - \left(v_{up} + v_{dn}\right) X_6 + J_{S,7} - J_{S,6}}{z_6}$$

$$\frac{dS_6}{dt} = \frac{\frac{Q_f \cdot S_f}{A} - \left(v_{up} + v_{dn}\right) S_6}{z_6}$$

Layers model (Tákacs *et al*., 1991)

Mass fluxes above *feed layer*

$$Q_{ef} \cdot X_{10}$$



$$J_{up,9} = v_{up} \cdot X_9$$

$$J_{S,10} = v_{S,10} \cdot X_{10}$$

$$J_{up,7} = v_{up} \cdot X_7$$

$$J_{S,8} = \min\left(v_{S,8} \cdot X_8, v_{S,9} \cdot X_9\right)$$

$$J_{up,6} = v_{up} \cdot X_6$$

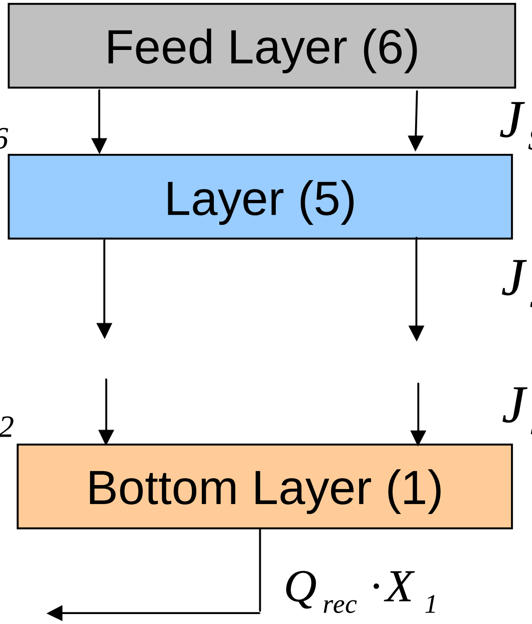
$$J_{S,7} = \min\left(v_{S,7} \cdot X_7, v_{S,8} \cdot X_8\right)$$

$$\frac{dX_7}{dt} = \frac{v_{up}\left(X_6 - X_7\right) + J_{S,8} - J_{S,7}}{z_7} \qquad \frac{dS_7}{dt} = \frac{v_{up}\left(S_6 - S_7\right)}{z_7}$$

$$\frac{dX_{10}}{dt} = \frac{v_{up}\left(X_9 - X_{10}\right) - J_{S,10}}{z_{10}} \qquad \frac{dS_{10}}{dt} = \frac{v_{up}\left(S_9 - S_{10}\right)}{z_{10}}$$

Layers model (Tákacs *et al*., 1991)

<u>Mass fluxes below ***feed layer***</u>



$$J_{dn,6} = v_{dn} \cdot X_6$$

$$J_{S,6} = \min\left(v_{S,6} \cdot X_6, v_{S,5} \cdot X_5\right)$$

$$J_{dn,5} = v_{dn} \cdot X_5$$

$$J_{S,5} = \min\left(v_{S,5} \cdot X_5, v_{S,4} \cdot X_4\right)$$

$$J_{dn,2} = v_{dn} \cdot X_2$$

$$J_{S,2} = v_{S,2} \cdot X_2$$

$$Q_{rec} \cdot X_1$$

$$\frac{dX_5}{dt} = \frac{v_{dn}\left(X_6 - X_5\right) + J_{S,6} - J_{S,5}}{z_5}$$

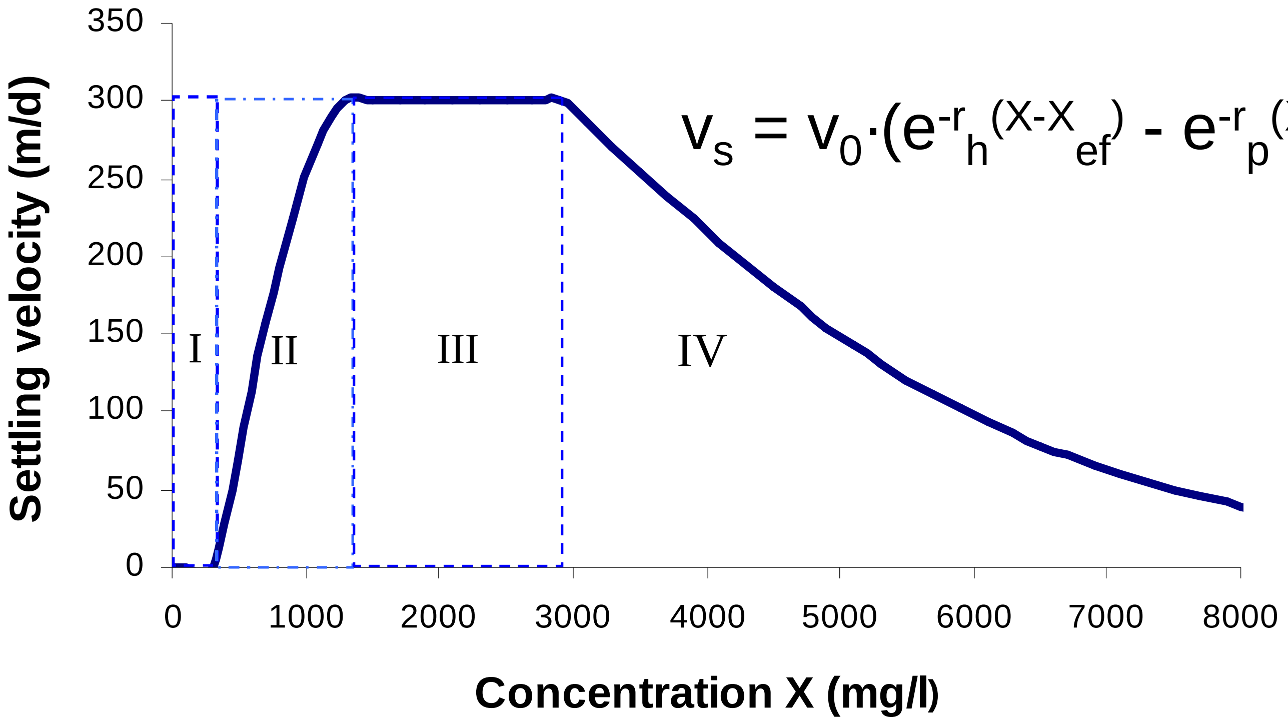
$$\frac{dS_5}{dt} = \frac{v_{dn}\left(S_6 - S_5\right)}{z_5}$$

$$\frac{dX_1}{dt} = \frac{v_{dn}\left(X_2 - X_1\right) + J_{S,2}}{z_1}$$

$$\frac{dS_1}{dt} = \frac{v_{dn}\left(S_2 - S_1\right)}{z_1}$$

Layers Model (Tákacs *et al.*, 1991)

Settling velocity (v_s)



$$v_s = v_0 \cdot (e^{-r_h (X - X_{ef})} - e^{-r_p (X - X_{ef})})$$

I: TSS reaches the minimum attainable concentration

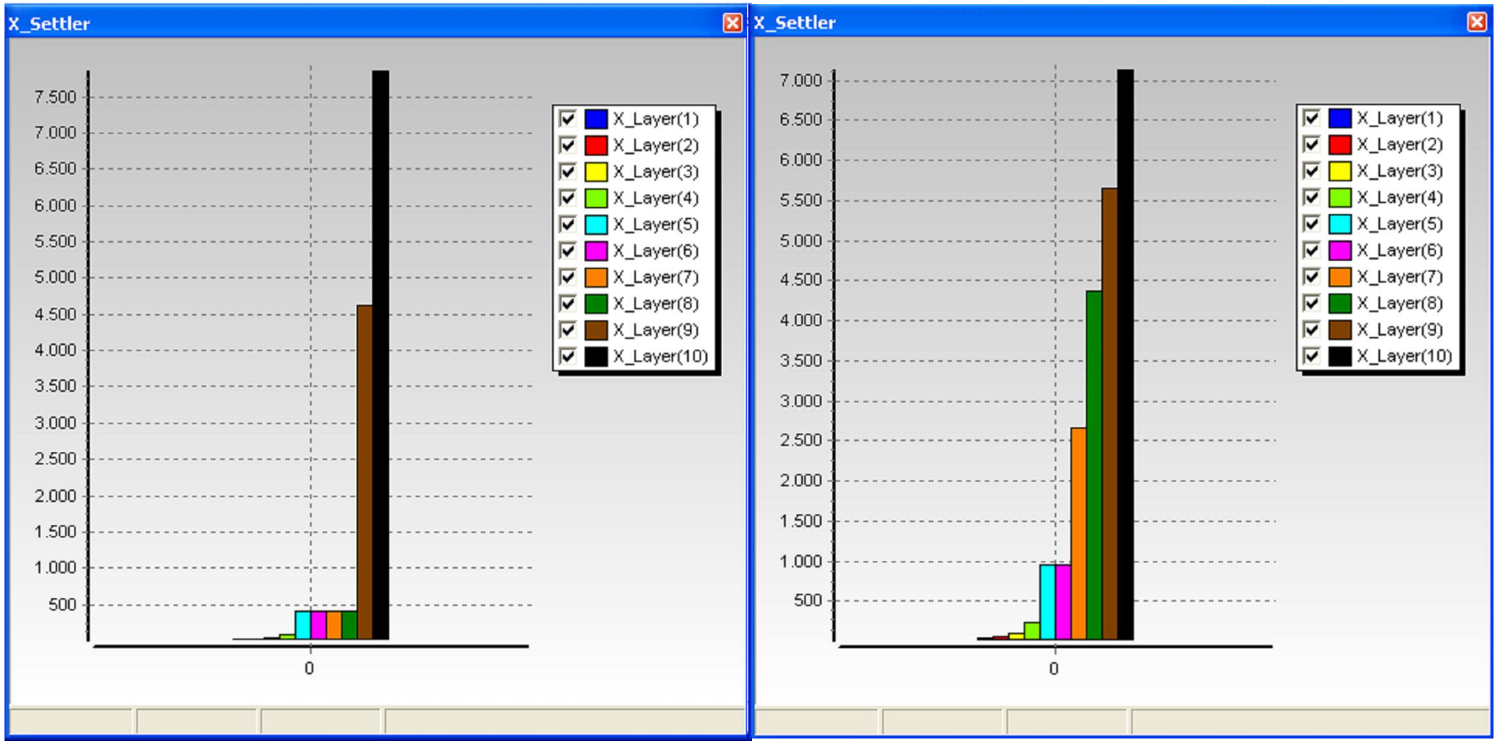
II: v_s is dominated by the slowly settling particles (v_s is sensitive to r_p)

III: v_s is independent of TSS. Floc particles reach their maximum size

IV: Thickening is dominating (v_s is sensitive to r_h)

Layers model (Tákacs *et al.*, 1991)

Example



Conclusions

- A correct design and operation of settlers is crucial points to achieve a good process performance in a WWTP
- Dynamic layer models are a useful tool for this purpose

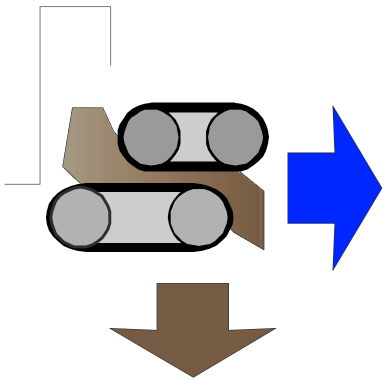
  Layer model (Tákacs et al., 1991) provides a uniform framework for the simulation of the clarification and thickening processes under both steady-state conditions and dynamic conditions

In BioWin3

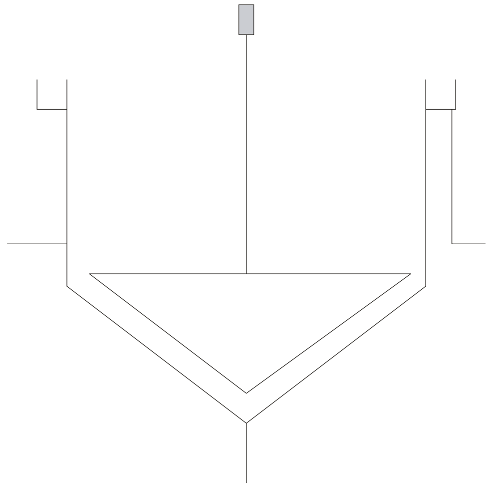
There are 3 types of models

1- **Point Separation Model**: simple mass calculation splitting the incoming solids into two streams. The user specifies a % of solid capture

Dewatering units

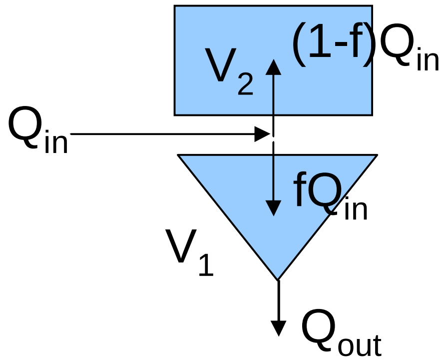


Point Clarifiers



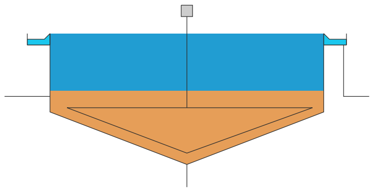
In BioWin3

2- **Ideal Separation Models**: The user defines the relative % of "thickened" or "sludge" volume and of "clarified" or liquid" volume of the separation unit



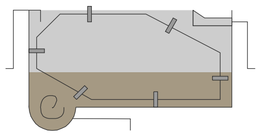
$$\frac{V_1 \partial C}{\partial t} = fQ_{In}C_{In} - Q_{out}C_{out}$$

Secondary settlers

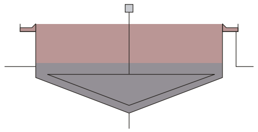


Primary settlers

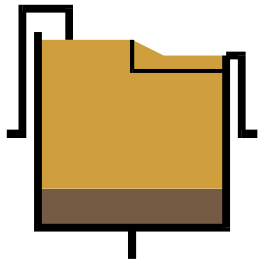
Simple



Activated



Grit Removal Tanks



In BioWin3

3-Flux Based Models: Solid and Liquid movement in the vertical dimension. Settler divided into a number of layers (typically 10).

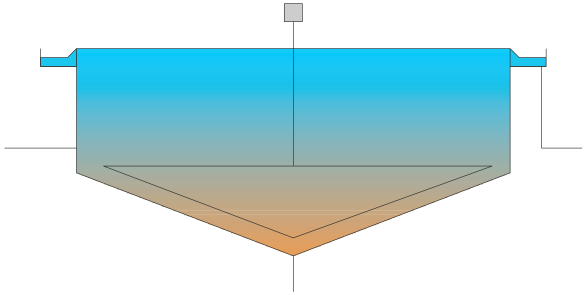
3 zones with different mass balance equations: (zone above the feed layer, feed layer, and zone below the feed layer)

Numerical methods to solve the mass balances

Two types of flux theory based models

- A) Vesilind
- B) Double Exponential (Takacs)

In BioWin3



Biowin 3 allows the user to set:

- Number of Layers
- Number of feed Layer
- Position of the feed layers
- Biological Reaction occurring in the sludge blanket
- Customize settling parameter (Vesilind & Takacs models)

In BioWin3

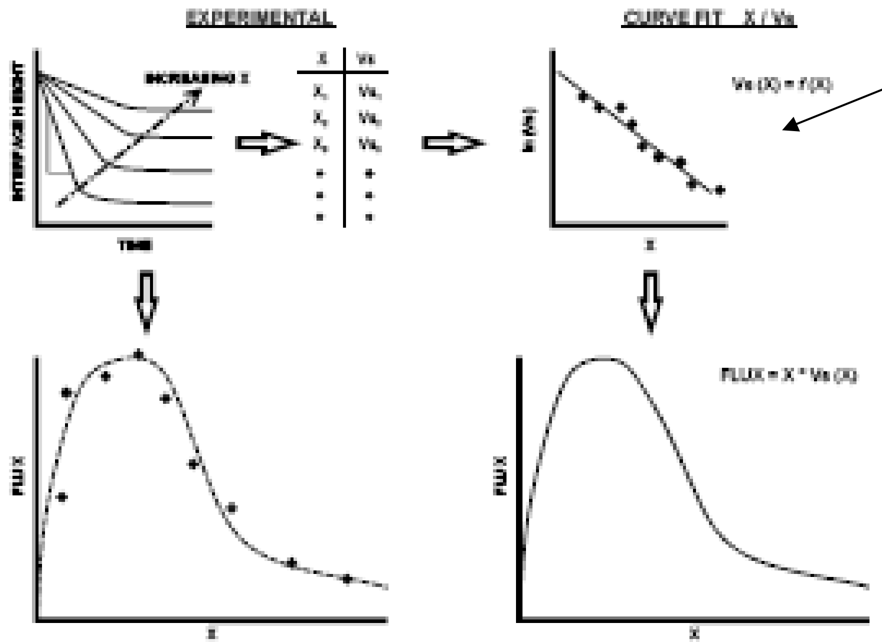
A) Vesilind equation for hindered settling

$$V_{S,I} = V_o e^{-kX_i}$$

Where V_o = Maximum settling velocity, K = settling parameter,

and X_i = TSS concentration in layer i

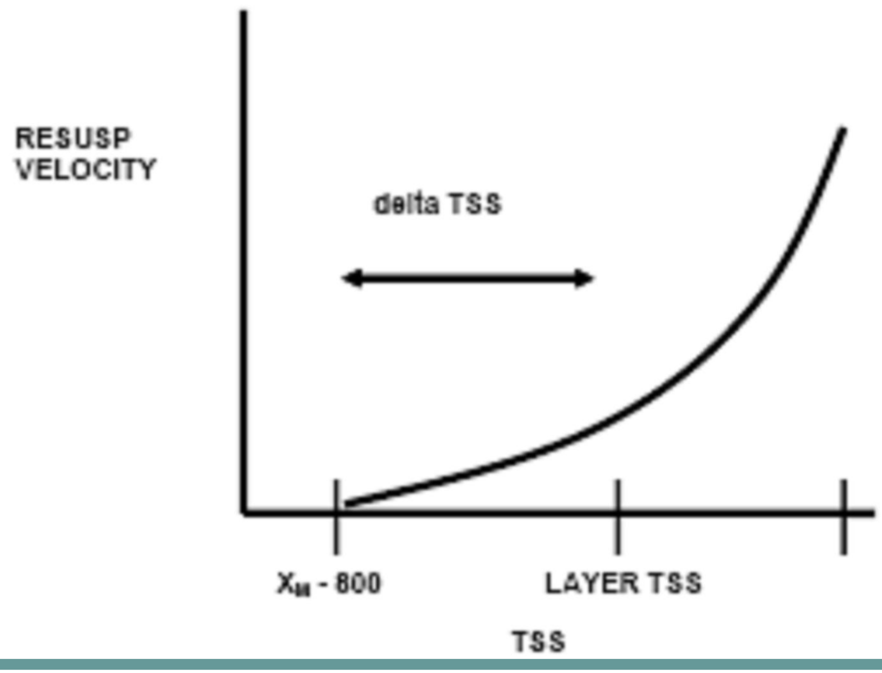
$$\ln V_S = \ln V_o - KX$$



Procedure used to obtain Vesilind settling velocity model parameters.

In BioWin3

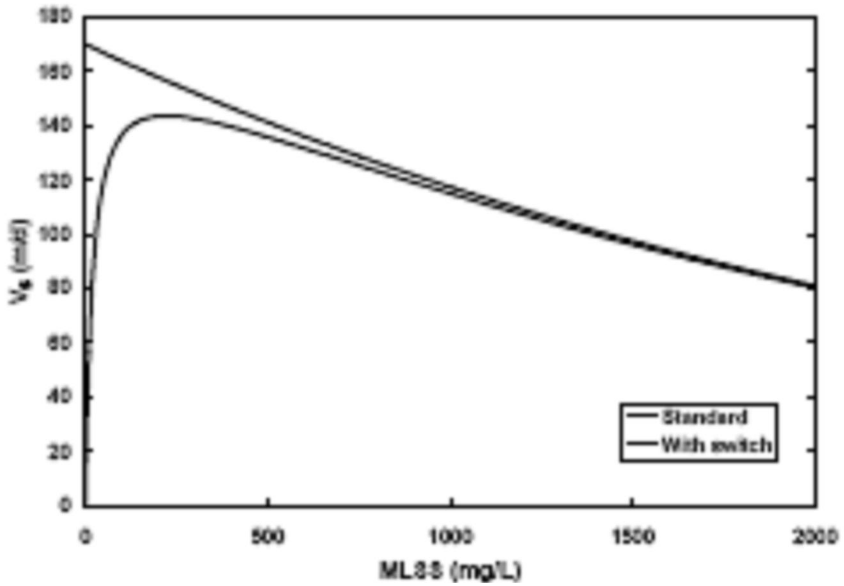
- Solid Resuspension occurs when TSS approaches maximum compactability. A resuspension model switches on at a maximum allowable concentration and is proportional to (TSS – Maximum compatability)^2



In BioWin3

- Vesilind equation overpredicts settling velocities at low TSS concentrations
- Biowin uses a Modified equation (Settling velocity switching function)

$$V_{S,I} = V_o e^{-KX_i} \cdot \left(\frac{X_i}{K_S - X_i} \right)$$



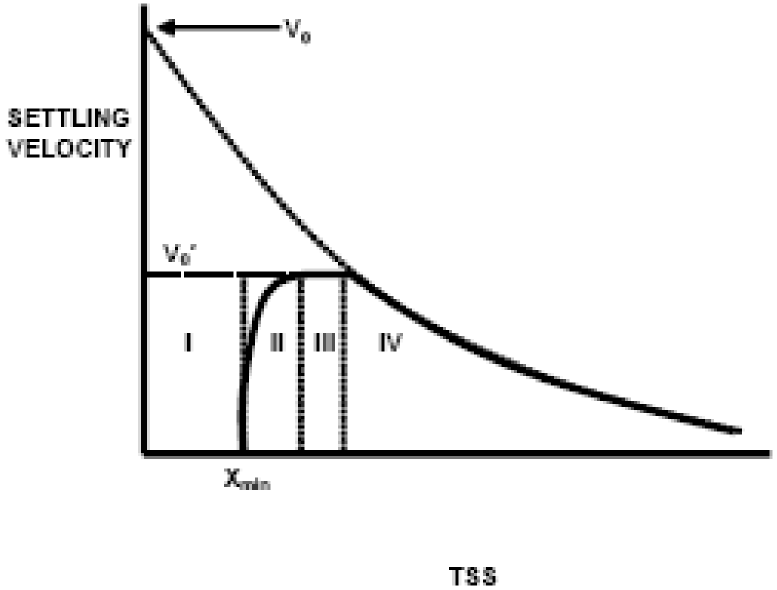
In BioWin3

B) Double Exponential Settling velocity

$$V_{S,I} = V_o e^{-K_h (X_i - X_{\min})} - V_o e^{-K_f (X_i - X_{\min})}$$

where $X_{\min}$ is the minimum attainable solid concentration (20 mg/L by default)

$$X_{\min} = f_{nss} X_f =$$



Assignment: Secondary Settler Design and Simulation in BioWin 3

The performance of a Secondary Settler of a WWTPs in a 6000 inhabitants town (4 inhabitants per house) was evaluated. The plant operates at a Q_R/Q = 0.45. The Design Sludge Concentration in the aeration tank recirculation is 12.000 g/m^3

A)-Determine the Sludge Settling Parameters

B)-Determine the Area needed by using the Methods of Tallmadge and Fitch and solid flux analysis.

C) Steady State simulation of the settler using BioWin 3

The characteristics of the effluent entering the secondary clarifier are:

BOD (mg/L)	2932
VSS (mg/L)	3000
TSS (mg/L)	3450
TKN (mg/L)	400
TP (mg/L)	40
Nitrate (mg/L)	2
pH	7.3
Alkalinity (mmol/L)	6
Calcium (mg/L)	80
Magnesium (mg/L)	15
DO (mg/L)	2
Fxsp	0.937
Fup	0.15

Results from Sludge Sedimentation Tests

The characteristics of the sludge were determined experimentally in Settling Tests in a column of 3 m

MLSS 3000 kg/m^3

H (m)	t (h)
3.00	0
2.65	0.1
2.30	0.2
2.00	0.3
1.76	0.4
1.53	0.5
1.32	0.6
1.15	0.7
1.00	0.8
0.88	0.9
0.76	1
0.66	1.1
0.57	1.2
0.50	1.3
0.45	1.4
0.42	1.5
0.40	1.6

MLSS (kg/m^3)	Vs (m/h)
2	4.4
3	3.5
4	2.6
5	1.8
6	1.2
7	0.8
8	0.55
9	0.37
10	0.28
15	0.12
20	0.06
30	0.027