Wastewater Treatment

Dr. Motasem Saidan

m.saidan@gmail.com

Wastewater Treatment

- **Wastewater:**
  - ➢ Usually refer to sewage treatment, or domestic wastewater treatment
  - ➢ process of removing contaminants from wastewater, both runoff and domestic

- **Wastewater comes from:**
  - Residences (kitchen, bathroom)
  - Commercial institution
  - Industrial institution (usually require specialized treatment process)

WW is collected and transported via a network of pipes and pump stations to a municipal treatment plant

Typical Wastewater Characteristics

Parameter	Concentration (mg/L)
Biochemical Oxygen Demand (BOD)	250
Total suspended solids (TSS)	250
Chemical oxygen demand (COD)	500
Nitrogen, Total	40
Ammonia	30
Organic	10
Nitrate	0
Phosphorus, Total	10
Ortho	6
Organic	4
Total organic carbon (TOC)	150
Chloride	50

An estimate of the flow rate : 600L/capita-day

❖ Purpose:

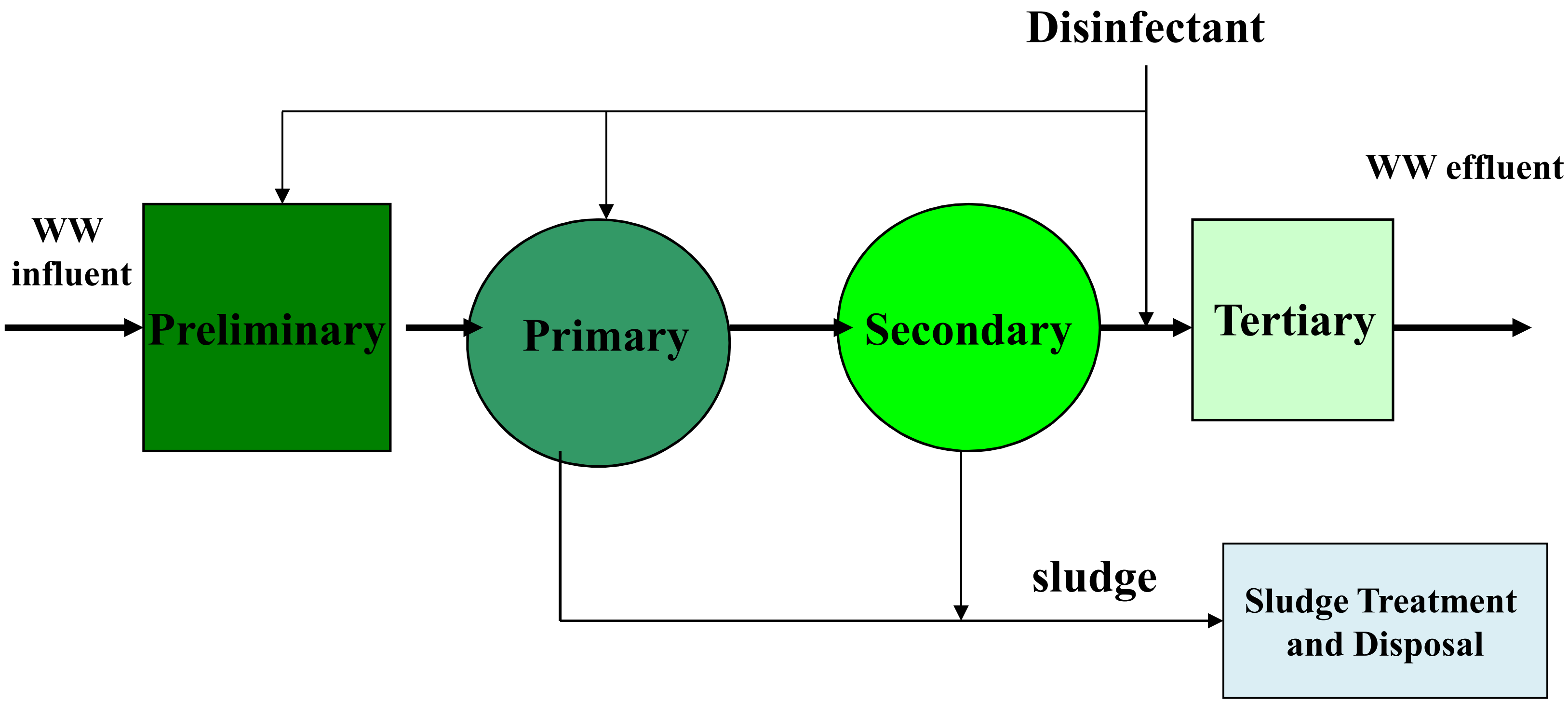
- To manage water discharged from homes, businesses, and industries to reduce the threat of water pollution.

- To reduce the amount of pollutants in the water to such a level that the water can be returned to the environment without causing stress on aquatic life and be of sufficient quality for subsequent users.

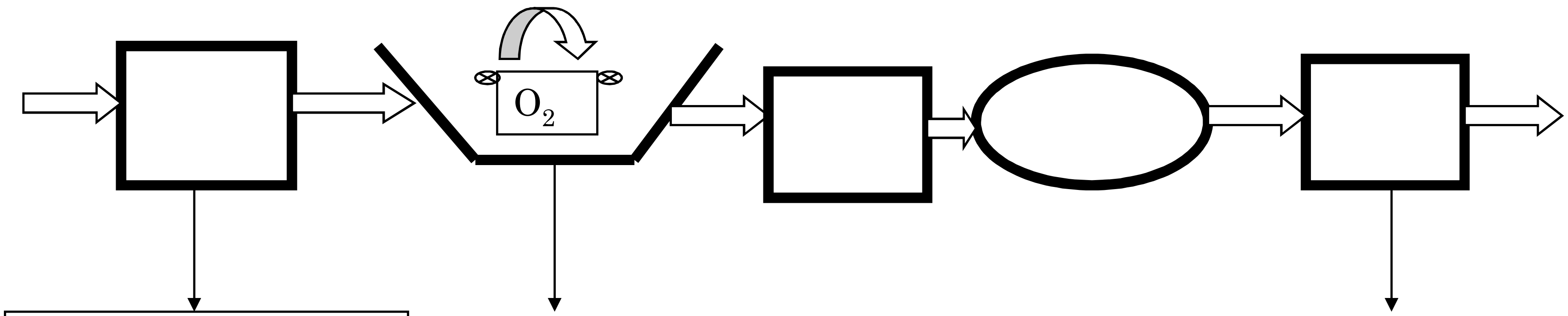
Types of Treatments

- **Mechanical treatment**
  - Influx (Influent)
  - Removal of large objects
  - Removal of sand and grit
  - Primary Sedimentation
- **Biological treatment**
  - Trickling bed filter
  - Activated sludge
- **Chemical treatment**
  - Disinfection

Wastewater treatment stages



Wastewater Treatment Processes



Primary treatment

- screening
- grit removal
- removal of oil
- sedimentation

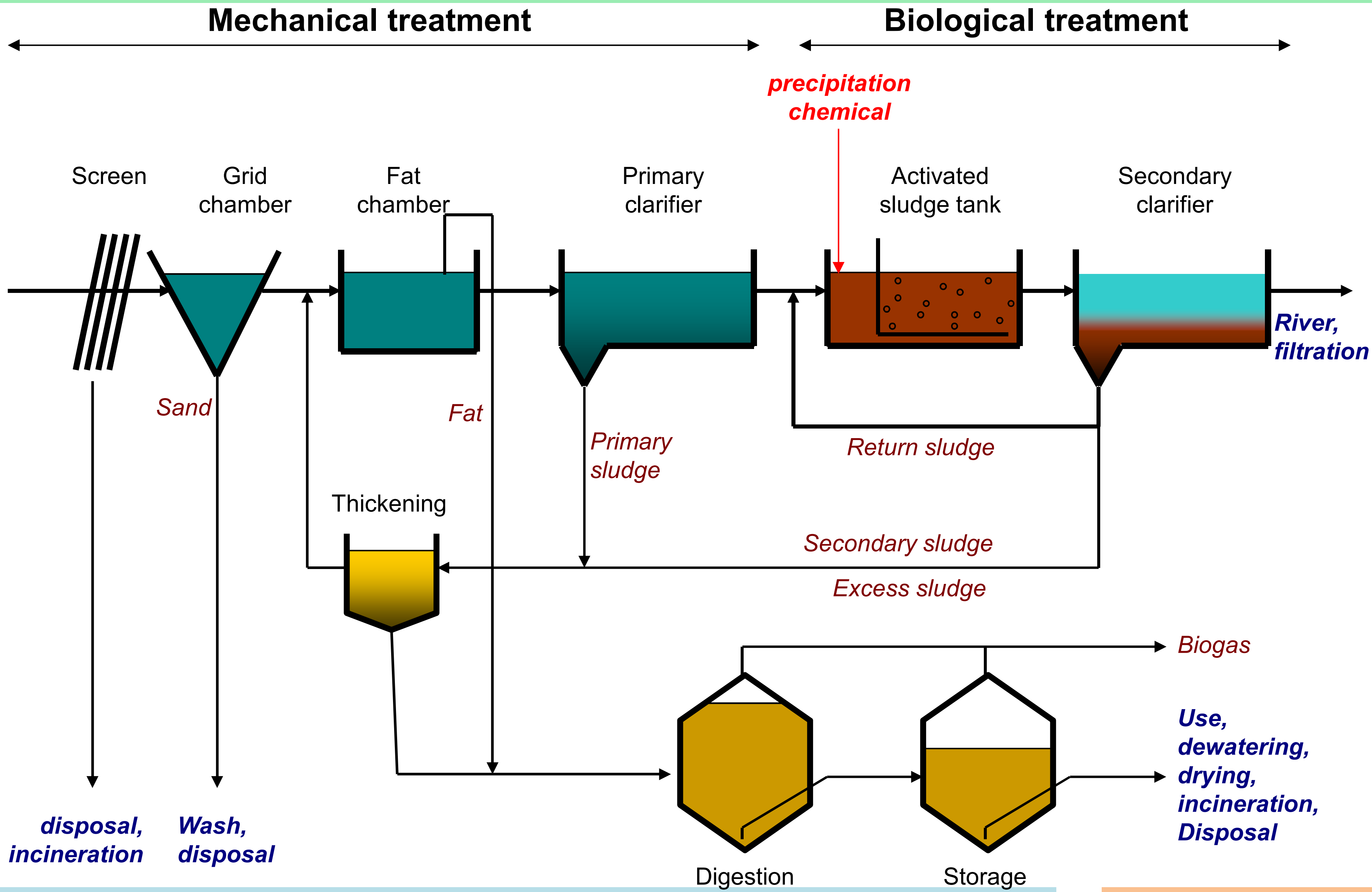
Secondary treatment

- Aerobic, anaerobic lagoons
- Trickling filter- activated sludge-oxidation ditch
- Mostly BOD removal technology

Tertiary treatment

- Nitrate removal
- Phosphorus removal
- Disinfection

Layout of a WWTP

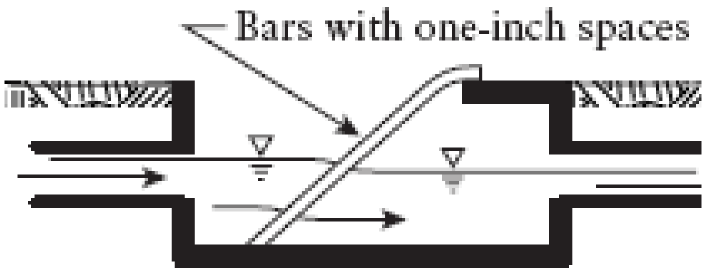


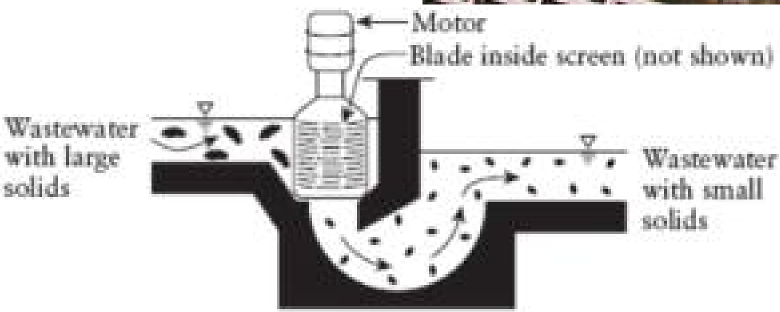
Preliminary Treatment

- removes large objects and non-degradable materials
- protects pumps and equipment from damage
- bar screen and grit chamber

- **Bar Screen**

catches large objects that have gotten into sewer system such as bricks, bottles, pieces of wood, etc

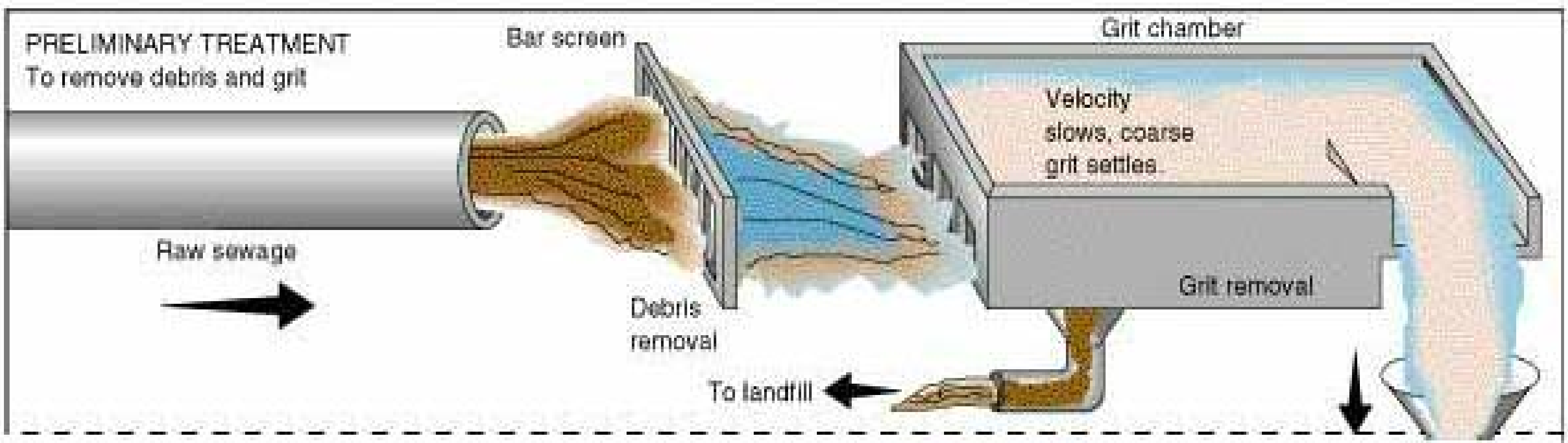




Preliminary Treatment

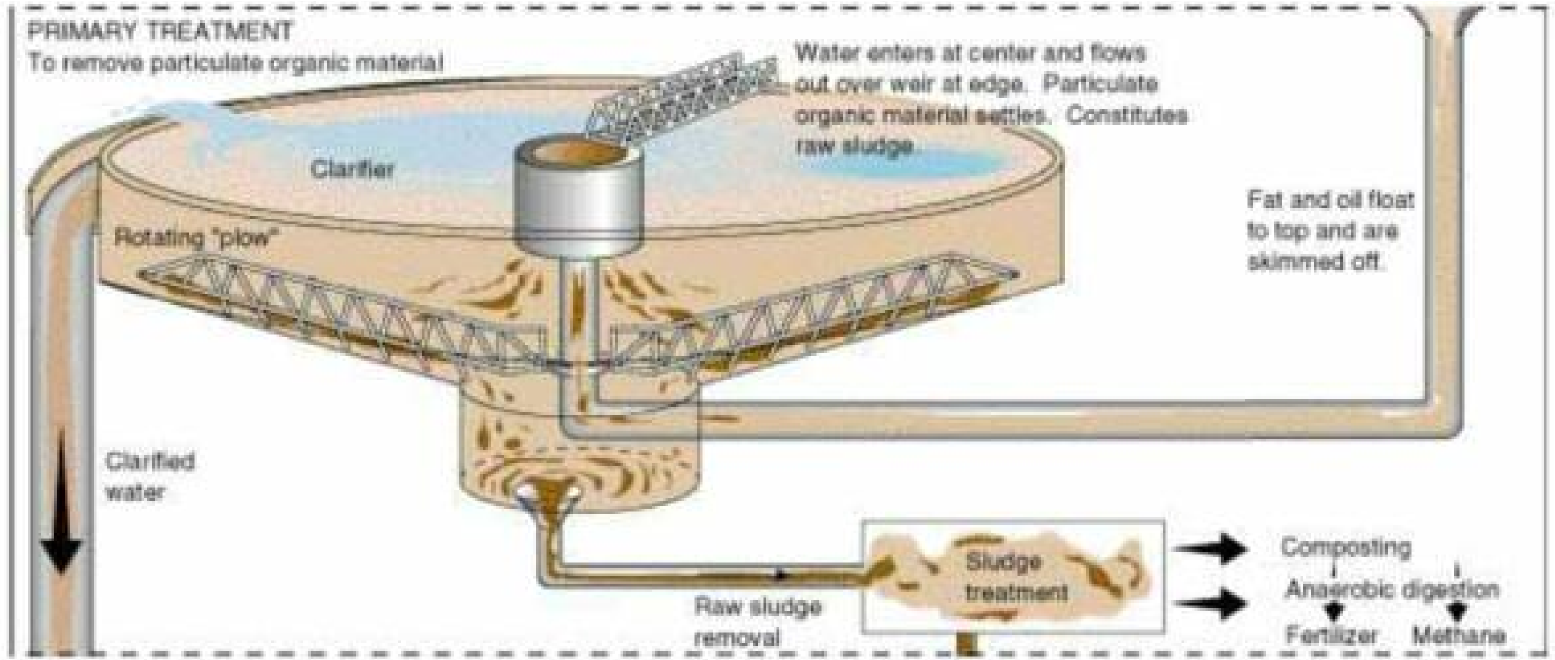
- Grit removal chamber : to removes rocks, gravel, broken glass, etc.

  - Grit is composed primarily of sand, cinders, and gravel
  - Grit causes excessive wear and abrasion in pipes and pumps
  - Grit accumulates in downstream tanks where flow velocities are insufficient to keep it in suspension. As grit accumulates, it reduces the effective tank volumes and thus treatment effectiveness
  - Grit removal is done by gravity settling (the high specific gravity of grit)



Primary Treatment

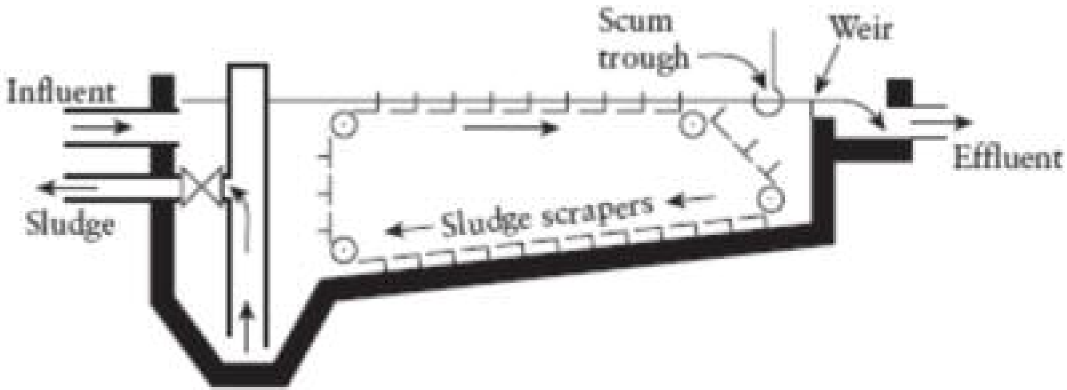
- a physical process
- wastewater flow is slowed down and suspended solids settle to the bottom by gravity
- the material that settles is called sludge or biosolids

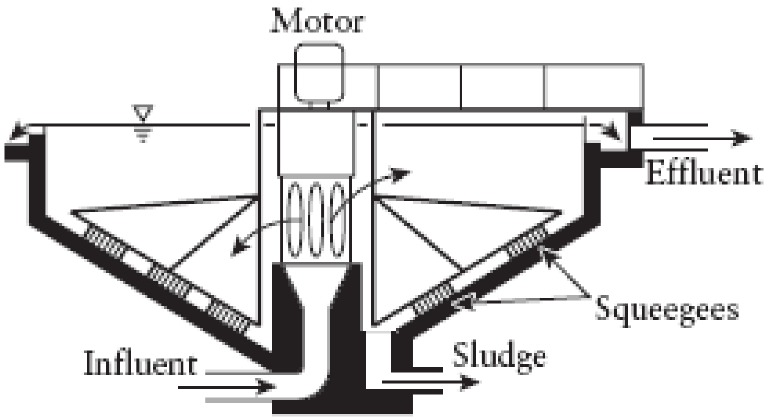


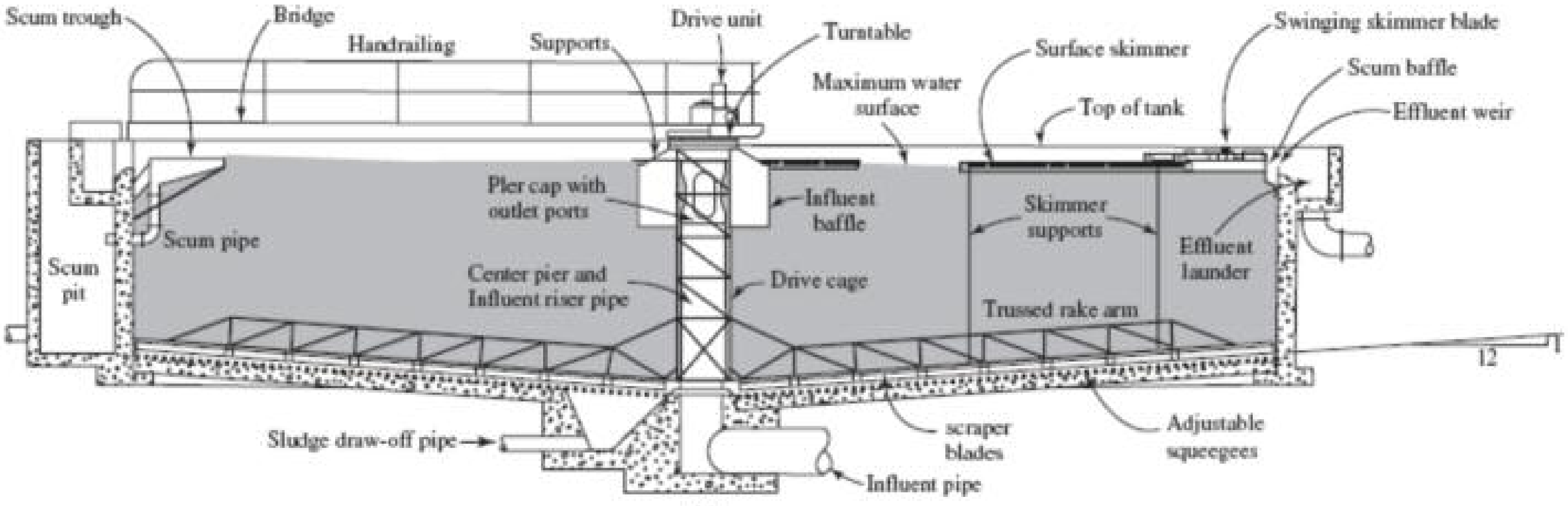
Sedimentation tanks and clarifiers

- The settling tank that follows preliminary treatment, such as screening and grit removal, is known as the *primary clarifier*.

- Primary treatment, in addition to removing about 60% of the solids, removes about 30% of the demand for oxygen and perhaps 20% of the phosphorus (both as a consequence of the removal of raw sludge).






Scum trough
Bridge
Handrailing
Supports
Drive unit
Turntable
Maximum water surface
Top of tank
Surface skimmer
Swinging skimmer blade
Scum baffle
Effluent weir
Scum pipe
Scum pit
Pier cap with outlet ports
Influent baffle
Skimmer supports
Effluent launder
Center pier and Influent riser pipe
Drive cage
Trussed rake arm
12
1
Sludge draw-off pipe
scraper blades
Adjustable squeegees
Influent pipe

(a)

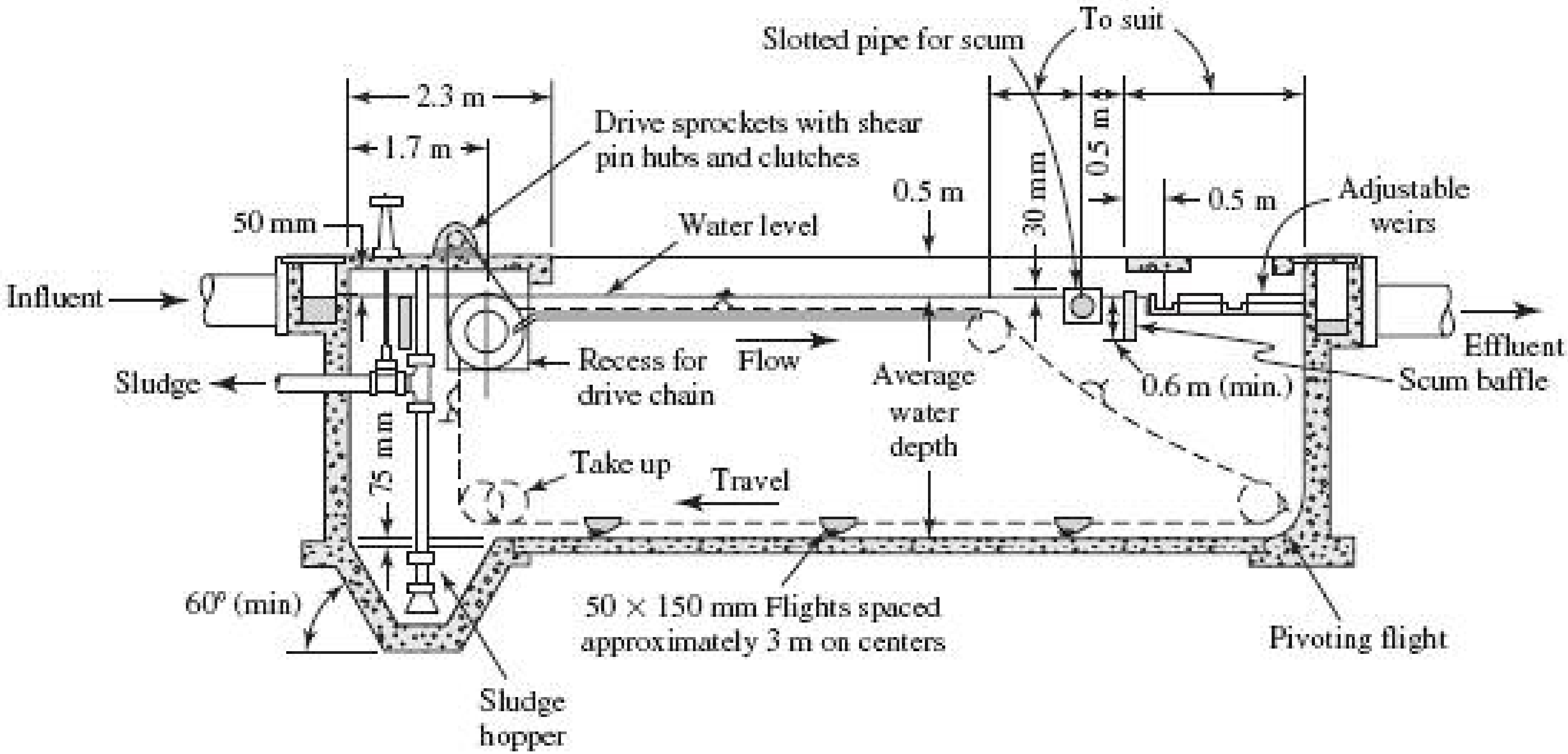
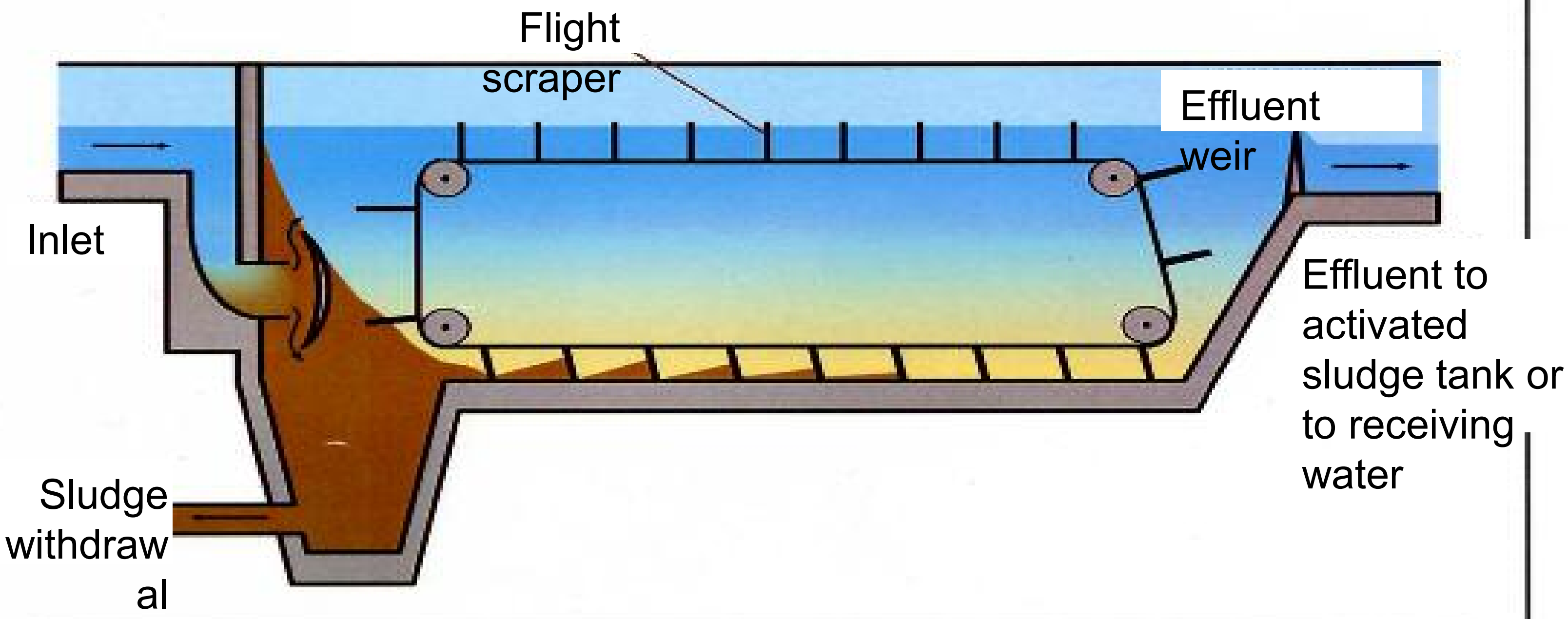


FIGURE 21-3
Rectangular primary settling tank. (*Source:* Davis and Cornwell, 2008.)

Primary / secondary clarifier



13 Umweltbereich Wasser

Primary Settling Tank Design

- Size:
  - rectangular: 3-24 m wide x 15-100 m long
  - circular: 3-90 m diameter
- Detention time: 1.5-2.5 hours
- Overflow rate: 25-60 $m^3/m^2 \cdot day$
- Typical removal efficiencies:
  - solids: 50-60%
  - BOD_5: 30-35%

Effects of primary clarifier on wastewater

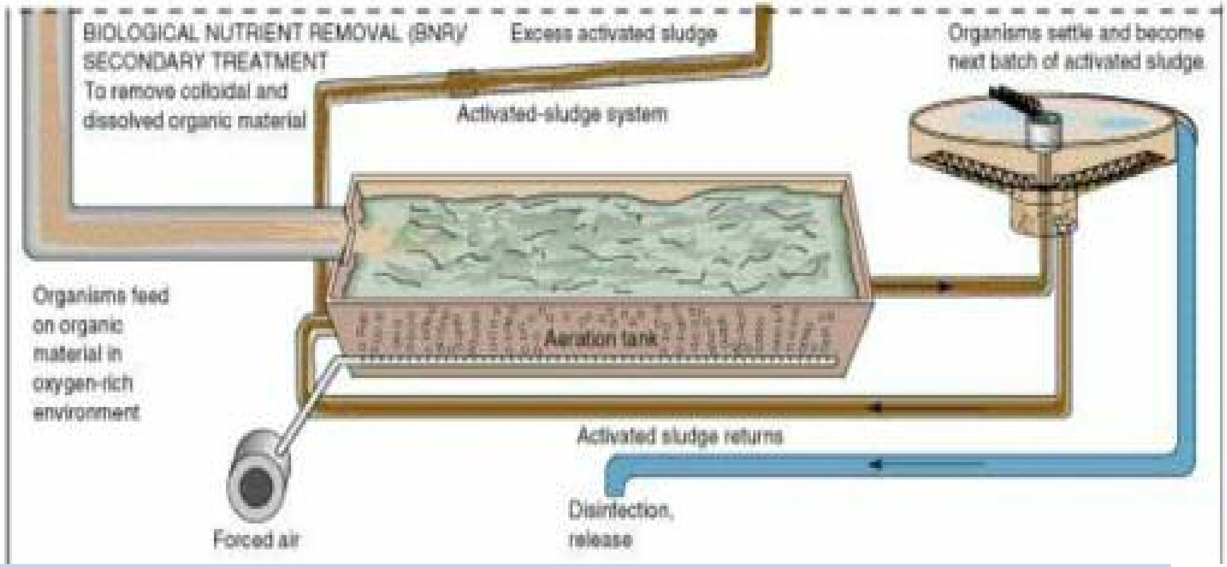
Compound	Unit	Inlet	Outlet*	$\eta = \frac{C_{in} - C_{out}}{C_{in}}$
TSS	g TSS / m^3	360	180	0.5
BOD_5	g O_2 / m^3	300	230	0.23
COD	g O_2 / m^3	600	450	0.25
TKN	g N / m^3	60	56	0.067
NH_4-N	g N / m^3	40	40	0
NO_2-N	g N / m^3	0	0	0
NO_3-N	g N / m^3	1	1	0
P_{tot}	g P / m^3	10	9	0.1
Alkalinity	mol HCO_3^- / m^3	= f(Drinking water) + NH_4-N		

* Short residence time

Secondary Treatment

- A Biological Process
- The objective of secondary treatment is to remove/reduce BOD using microbial action from soluble to suspended solids.

Organic Matter + Bacteria + O_2 $\rightarrow$ New Cells (Biomass) + H_2O, CO_2, NH_3



Biological wastewater treatment

Classification of biological Wastewater methods

Suspended and attached

Suspended growth process is a biological w.w.t in which microorganisms are maintained in suspension while converting organic matter to gases and cell tissue (Activated sludge).

Attached growth is a biological w.w.t in which microorganisms responsible for the conversion of organic matter to gases and cell tissue are attached to some material such as rocks, sand, or plastic (Trickling filter).

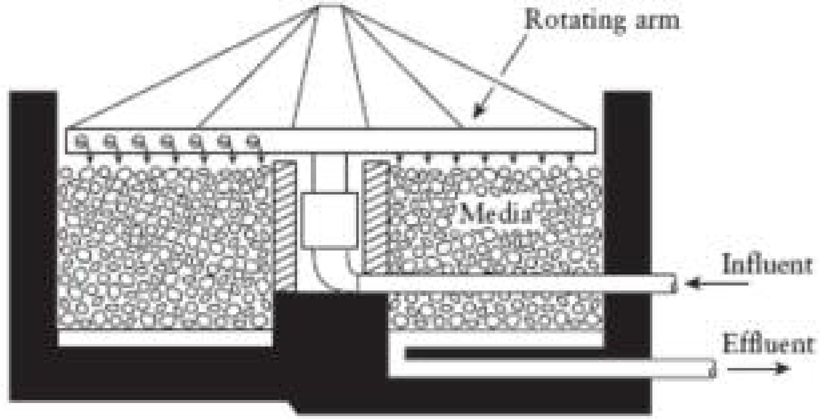
Aerobic and anaerobic

Aerobic: biological treatment is a process in which the pollutants in the waste water (organic matter) are stabilized by microorganisms in the presence of molecular oxygen

Anaerobic: biological treatment is a process in which the pollutants in the waste water (organic matter) are stabilized by microorganisms in the absence of molecular oxygen

Secondary Treatment Method

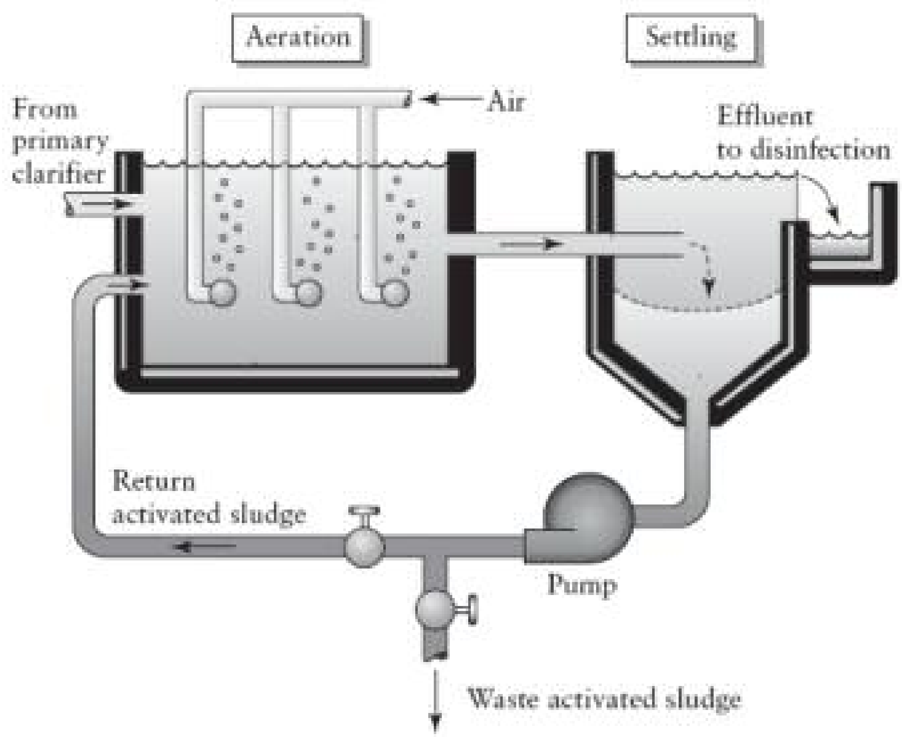
The Trickling filter



- It does not "filter" the water
- It consists of a bed of media (such as fist-sized rocks or various plastic shapes) over which the waste is trickled
- An active biological growth forms on the media, and the organisms obtain their food from the waste stream dripping over the bed.
- Air is either forced through the media
- Wastewater is sprayed and runs over a plastic media and organisms clinging to the media remove organic matter from the wastewater.

Activated sludge system

- Air is bubbled into this tank (called the *aeration tank*)
- The microorganisms use the energy and carbon by decomposing this material to CO_2 and H_2O.
- The microorganisms are separated from the liquid in a settling tank, called a *secondary* or *final clarifier*



- The separated microorganisms exist on the bottom of the final clarifier without additional food and become hungry waiting for more dissolved organic matter. These microorganisms are said to be ***activated.***

Final Clarifier

- The activated sludge process is a continuous operation
- one of the end products of this process is excess microorganisms. If the microorganisms are not removed, their concentration eventually increases to the point where the system is clogged with solids.

Basic Ingredients & Conditions

- High density of microorganisms (keep organisms in system)
- Good contact between organisms and wastes (provide mixing)
- Provide high levels of oxygen (aeration)
- Favorable temperature, pH, nutrients (design and operation)
- No toxic chemicals present (control industrial inputs)

Biological Growth Type

- **Suspended Growth –Activated Sludge**
  - Bacteria are kept in suspension by mixing
  - Sludge age is controlled by reactor volume or biomass recycle following sedimentation
- **Attached Growth – Biofilter (Trickling Filters , Rotating Biological Contactors)**
  - Bacteria are attached on supporting media or entrapped between supporting media

Dispersed growth vs. Fixed Growth

- ***Dispersed Growth** –suspended organisms*
  - ✓ Activated sludge
  - ✓ Oxidation ditches/ponds
  - ✓ Aerated lagoons, stabilization ponds
- ***Fixed Growth** –attached organisms*
  - ✓ Trickling filters
  - ✓ Rotating Biological Contactors (RBCs)

Design of Activated Sludge Systems

- Wastewater is aerated in a tank
- Bacteria are encouraged to grow by providing
  - Oxygen
  - Food (BOD)
  - Nutrients
  - Correct temperature
  - Time

- As bacteria consume BOD, they grow and multiply
- Treated wastewater flows into secondary clarifier
- Bacterial cells settle, removed from clarifier as sludge
- Part of sludge is recycled back to activated sludge tank, to maintain bacteria population
- Remainder of sludge is wasted

The microbial growth curve

Biochemical reaction

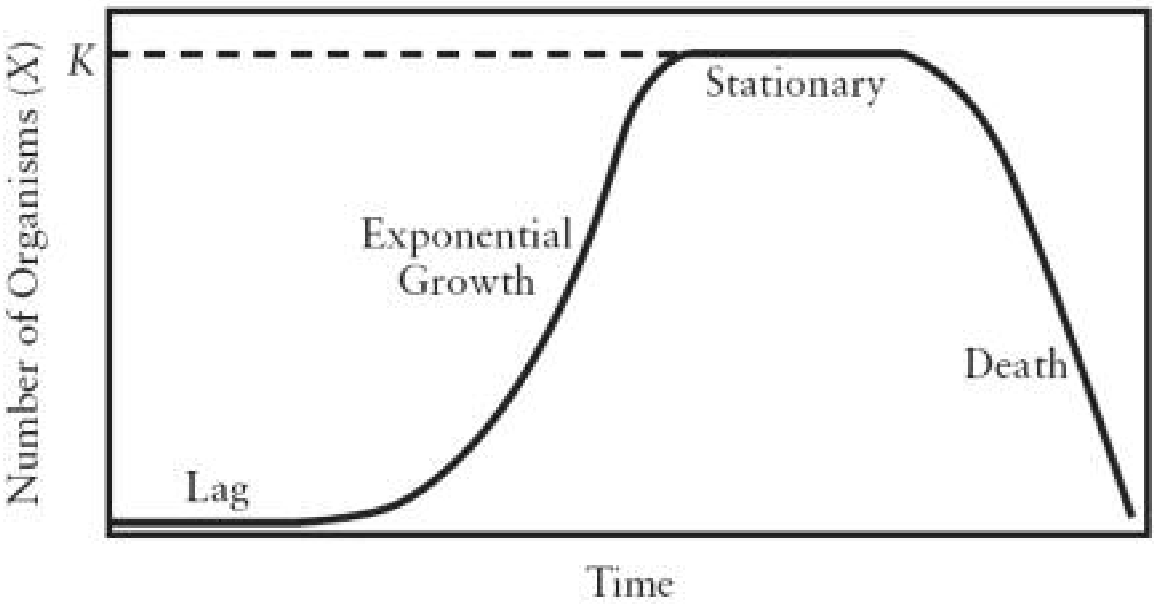
$$Food + O_2 + nutrients \xrightarrow{Bacteria} CO_2 + NH_3 + new \cdot biomass + other \cdot end \cdot products$$

Nutrients such as carbon, nitrogen, phosphorus, sulfur, and the elements required for the synthesis of proteins, nucleic acids, and other structural parts of the cells

The number of microorganisms is proportional to the growth rate:

$$\frac{dX}{dt} = \mu X$$

$$X = X_0 e^{\mu t}$$

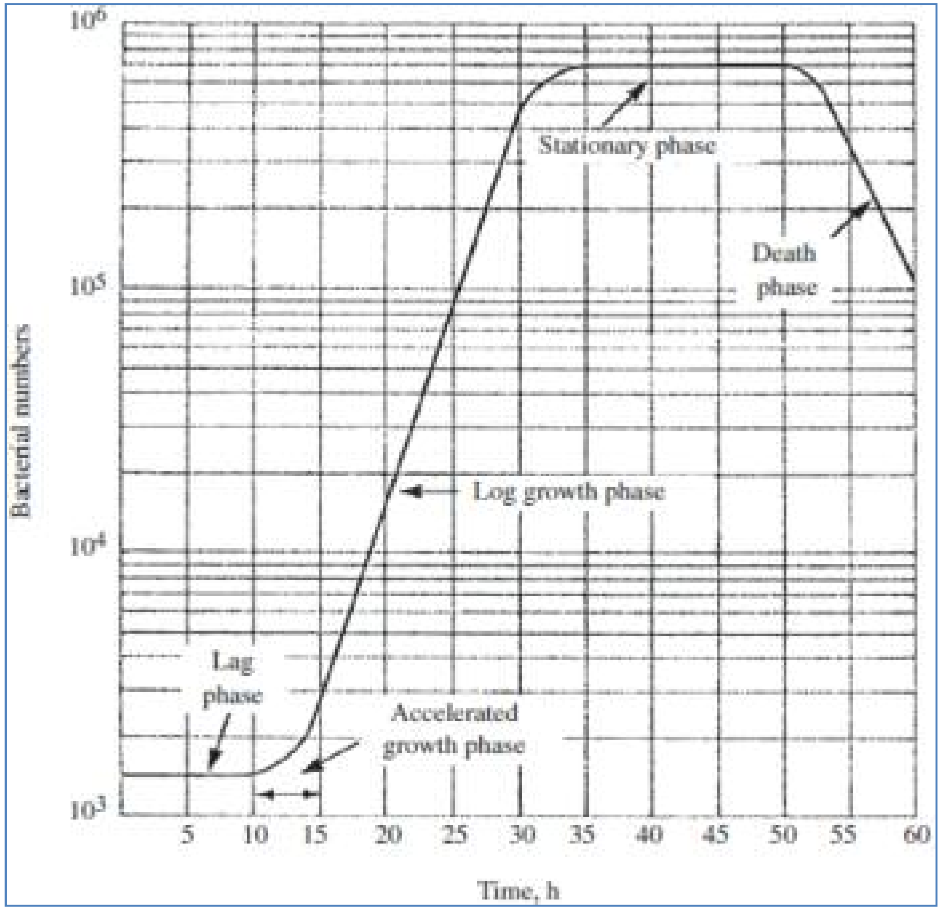


where X = number of microorganisms

μ = instantaneous, specific growth rate

- Bacteria reproduction is by binary fission (each cell divides producing two new cells), the increase in population follows in geometric progression:
  1 → 2 → 4 → 8 → 16 → 32, etc.

- The log growth phase tapers off as the substrate becomes exhausted or as toxic byproducts build up. Thus, at some point the population becomes constant either as a result of cessation of fission or a balance in death and reproduction rates. This is depicted by the stationary phase on the growth curve.



- Following the stationary phase, the bacteria begin to die faster than they reproduce. This death phase is due to a variety of causes that are basically an extension of those that lead to the stationary phase.

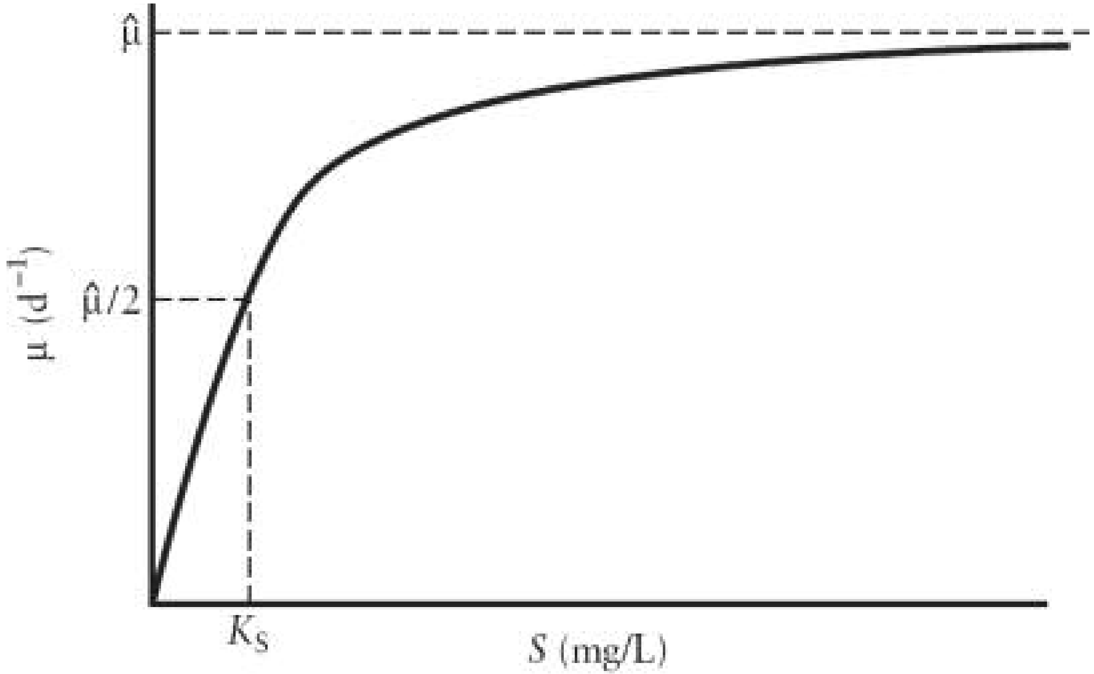
The Monod Equation

$$\mu = \hat{\mu} \frac{S}{K_S + S}$$

where $\hat{\mu}$ = maximum specific growth rate (at nutrient saturation)
S = substrate or nutrient concentration
K_S = saturation, or half-velocity, constant

Two constants are used to describe the growth rate:

- μ (mg/L) is the maximum growth rate constant (the rate at which the substrate concentration is not limiting)
- K_s is the half-saturation constant (mg/L) (i.e., concentration of S when μ = μ/2



Biomass production

$$\frac{dX}{dt} = growth \cdot rate - death \cdot rate = \mu X - k_d X$$

Where k_d represents the endogenous decay rate (d^{-1}) (i.e., microorganism death rate).

Substituting the growth rate constant:

$$\frac{dX}{dt} = \left(\frac{\mu_m S}{K_s + S} \right) X - k_d X$$

- Substrate utilization

$$-\frac{dS}{dt}=\frac{1}{Y}\frac{dX}{dt}$$

Where Y is the yield factor

(mg of biomass produced/mg of food consumed)

- Y range:

  Aerobic: 0.4 - 0.8 mg/mg

  Anaerobic: 0.08 – 0.2

$$\frac{dS}{dt}=\frac{1}{Y}\frac{dX_{growth}}{dt}=\frac{1}{Y}\left(\frac{\mu_m SX}{K_s+S}\right)$$

- Food to microorganism ratio (F/M)

  - Represents the daily mass of food supplied to the microbial biomass, X, in the mixed liquor suspended solids, MLSS
  - Units are Kg BOD_5/Kg MLSS/day

$$\frac{F}{M} = \frac{BOD_5(Kg/m^3)\,x\,Influent \cdot flow(m^3/d)}{ReactorSolids(Kg/m^3)\,x\,ReactorVolume(m^3)}$$

$$F/M = \frac{QS_0}{VX} = \frac{S_0}{\bar{t}X}$$

Where hydraulic retention time,

$$\theta_C = \frac{VX}{QX} = \frac{V}{Q}$$

$$\bar{t} = \frac{V}{Q}$$

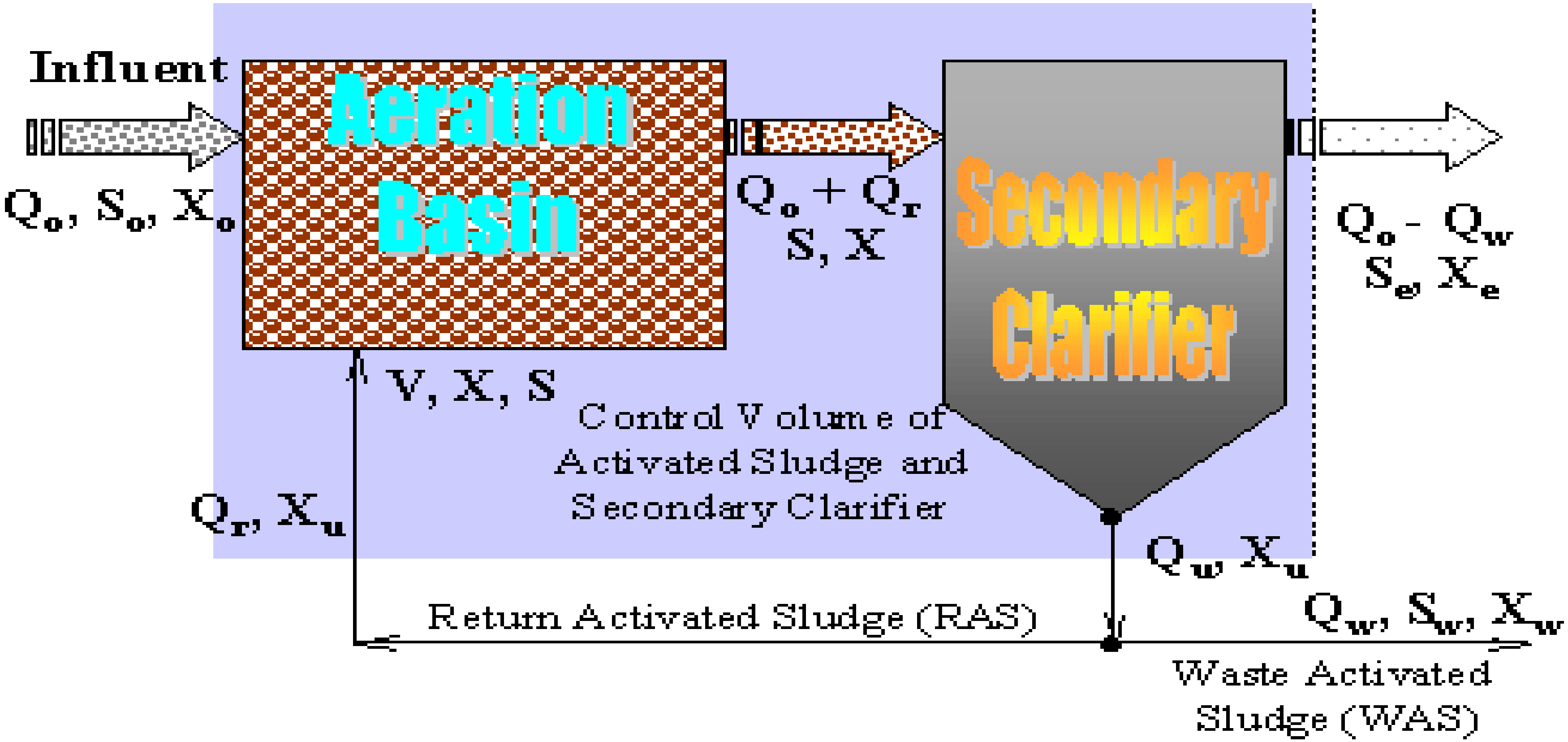
> ➢ Typical F/M ratio is between 0.2 – 0.5 kg BOD5/Kg MLSS/day

Design Parameters for ASS

Design parameters for activated sludge treatment processes

Type of process	Mean cell residence time (days)	F/M (kg BOD_5/ kg MLSS)	Loading (kg/BOD_5/ m^3-d)	Hydraulic retention time (hr)	MLSS (mg/L)	Recycle ratio
Conventional	5 - 15	0.2 - 0.4	0.3 - 0.6	4 - 8	1500 - 3000	0.25 - 1.0
Step aeration	5 - 15	0.2 - 0.4	0.6 - 1.0	3 - 5	2000 - 3500	0.25 - 0.75
Completely mixed	5 - 30	0.1 - 0.6	0.8 - 2.0	3 - 6	2500 - 4000	0.25 - 1.5
Contact stabilization	5 - 15	0.2 - 0.6	1.0 - 1.2	0.5 (contact) 3 - 6 (stabil.)	1000 - 3000 4000 - 10000	0.50 - 1.5
High-rate	5 - 10	0.4 - 1.5	1.6 - 16	2 - 4	4000 - 10000	1.0 - 5.0
Extended aeration	20 - 30	0.05 - 0.15	0.16 - 0.4	18 - 36	3000 - 6000	0.75 - 1.5
Pure oxygen	8 - 20	0.25 - 1.0	1.6 - 3.2	1 - 3	3000 - 8000	0.25 - 0.5

AS Design Equations



Mass balance of biomass production (CSTR)

Influent biomass + biomass production = effluent biomass + sludge wasted

$$Q_o X_o + V\frac{dX}{dt} = (Q_o - Q_w)X_e + Q_w X_w$$

Substitute biomass production equation

$$Q_o X_o + V\left(\frac{\mu_m S}{K_s + S} X - k_d X\right) = (Q_o - Q_w)X_e + Q_w X_w$$

Assume that influent and effluent biomass concentrations are negligible and solve

$$\frac{\mu_m S}{K_s + S} = \frac{Q_w X_w}{VX} + k_d$$

Mass balance of food substrate

Influent substrate + substrate consumed = effluent substrate + sludge wasted substrate

$$Q_o S_o + V\frac{dS}{dt} = (Q_o - Q_w)S_e + Q_w S_w$$

Substitute substrate removal equation

$$Q_o S_o + \frac{V}{Y}\left(\frac{\mu_m XS}{K_s + S}\right) = (Q_o - Q_w)S_e + Q_w S_w$$

Assume that no biochemical action takes place in clarifier. Therefore the substrate concentration in the aeration basin is equal to the substrate concentrations in the effluent and the waste activated sludge. Solve:

$$\frac{\mu_m S}{K_s + S} = \frac{Q_o Y}{VX}(S_o - S)$$

Overall equations

- Combine the mass balance equations for food and biomass:

$$\frac{Q_w V_w}{VX} + k_d = \frac{Q_o Y}{VX}(S_o - S)$$

The cell residence time is:

$$\theta_c = \frac{VX}{Q_w X_w}$$

and the hydraulic retention time is, $\theta = V/Q_o$

Substitute and rearrange:

$$X = \frac{\theta_c (Y)(S_o - S)}{\theta(1 + k_d \theta_c)}$$

Compute the F/M ratio

$$\frac{F}{M} = \frac{S_o}{\theta X}$$

$$\frac{F}{M} = \frac{S_o}{(V/Q_o)X} = \frac{Q_o S_o}{VX}$$

Values of growth constants for domestic wastewater

		Value[a]	
Parameter	Basis	Range	Typical
K_s	mg/L BOD5	25–100	60
k_d	d^{-1}	0–0.30	0.10
μ_m	d^{-1}	1–8	3
Y	mg VSS/mg BOD_5	0.4–0.8	0.6

[a]Values are for 20°C

Sources: Metcalf & Eddy, 2003; and Shahriar et al., 2006.

Ref. Book: Vesilind

Example: 11.1
Example: 11.2
Example: 11.3
Example: 11.4
Example: 11.5

Phosphorus Removal

- Phosphorus is typically found as mono-hydrogen phosphate (HPO_4^{2-}) in wastewater.

- The removal of phosphorus to prevent or reduce eutrophication is typically accomplished by chemical precipitation using one of three compounds.
- The precipitation reactions for each are shown below:

- ferric chloride: $FeC1_3 + HPO_4^{2-} = FePO_4 + H^+ + 3\ C1^-$
- alum: $Al_2(SO_4)_3 + 2\ HPO_4^{2-} = 2\ AlPO_4 + 2\ H^+ + 3\ SO_4^{2-}$
- lime:

  $5\ Ca(OH)_2 + 3\ HPO_4^{2-} = Ca_5(PO_4)_3OH + 3\ H_2O + 6\ OH^-$

- You should note that ferric chloride and alum reduce the pH while lime increases it.

  - The effective range of pH for alum and ferric chloride is between 5.5 and 7.0.

  - If there is not enough naturally occurring alkalinity to buffer the system to this range, then lime must be
  added to counteract the formation of H^+.

- The precipitation of phosphorus requires:
  - a reaction basin and
  - a settling tank to remove the precipitate.

- When ferric chloride and alum are used, the chemicals may be added directly to the aeration tank in the activated sludge system.
  - Thus, the aeration tank serves as a reaction basin
  - The precipitate is then removed in the secondary clarifier with biological solids.

- This is not possible with lime since the high pH required to form the precipitate is detrimental to the activated sludge organisms !!

- In some wastewater treatment plants, the $FeCl_3$ (or alum) is added before the wastewater enters the primary sedimentation tank.
  - This improves the efficiency of the primary tank
  - But: this may deprive the biological processes of needed nutrients.

Nitrogen Control

- Nitrogen in any soluble form (NH_3, NH_4^+, NO_2^-, and NO_3^-, but not N_2 gas) is a nutrient and may need to be removed from wastewater to help control algae growth in the receiving body.

- In addition, nitrogen in the form of ammonia:
  - exerts an oxygen demand and
  - can be toxic to fish.

- Removal of nitrogen can be accomplished either biologically or chemically:
  - The biological process is called *nitrification/denitrification*.
  - The chemical process is called *ammonia stripping*.

Nitrification/de-nitrification (Bio.):

- The natural nitrification process can be forced to occur in the activated sludge system by maintaining a cell detention time of 15 days or more.

- The nitrification step is expressed in chemical terms as follows:

$$NH_4^+ + 2\,O_2 = NO_3^- + H_2O + 2H^+$$

- Bacteria must be present to cause the reaction to occur. This step satisfies the oxygen demand of the ammonium ion.

  - If the nitrogen level is not of concern for the receiving body, then
  - wastewater can be discharged after settling.

  - If nitrogen is of concern, the nitrification step must be followed by anoxic denitrification by bacteria:

$$2\,NO_3^- + \text{organic matter} = N_2 + CO_2 + H_2O$$

Ammonia stripping (chem.):

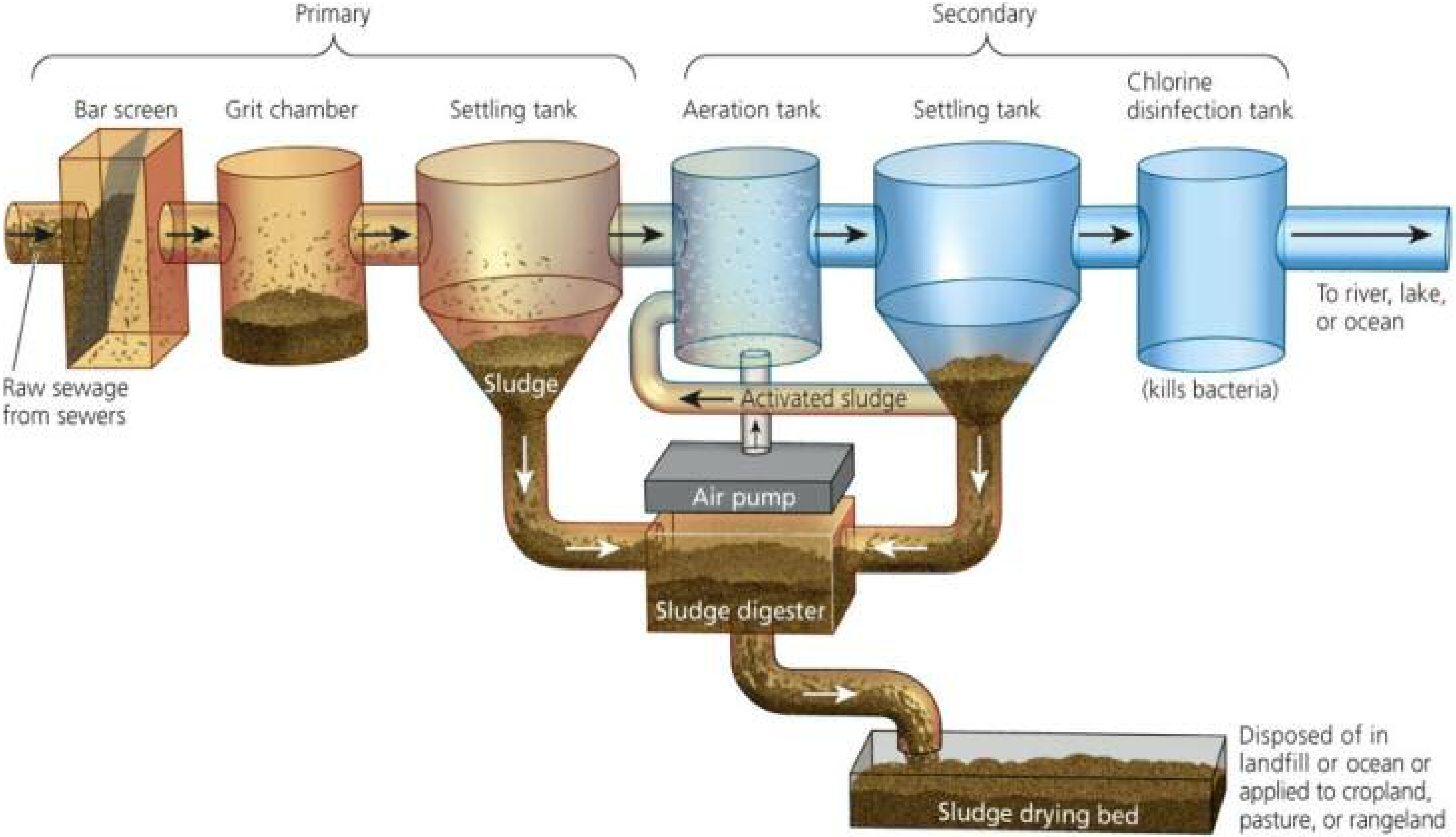
- Nitrogen in the form of ammonia can be removed chemically from water by
  - raising the pH to convert the ammonium ion into ammonia gas.
  - NH_3 then be stripped from the water by passing large quantities of air through the water.

The ammonia stripping reaction is:

$$NH_4^+ + OH^- = NH_3 + H_2O$$

- The hydroxide is usually supplied by adding lime:
  - Lime also reacts with CO_2 in the air and water to form a calcium carbonate scale, which must be removed periodically.

Wastewater treatment plant



Considerations for wastewater treatment plants

- costs
  - Capital (purchase, installation)
  - operation and maintenance (including energy)
- availability of space
- degree of treatment required by local Government permit
- municipal or municipal plus industrial
- Flow rate
- distance from residential areas (Problems of odor, flies, other nuisances…).
- agricultural usage or land application options
- presence of pathogens
- experience of design engineers