ENVE 302

Environmental Engineering Unit Processes

CHAPTER: 4

Activated Sludge Processes

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Suspended Growth (Activated Sludge) Treatment Process Configurations

Basic activated sludge process consists of the following 3 basic components:

1. A reactor in which the microorganism responsible for treatment are kept in suspension and aerated

2. Liquid-solids seperation in a sedimentation tank

3. A recycle system for returning solids removed from the liquid-solids seperation unit back to the reactor (to maintain a sufficient conc of biomass in the aeration tank)

Types of activated-sludge process

(i) Complete mix reactors

(ii) Plug flow reactors

(iii) Sequencing batch reactors

Complete mix activated sludge processes

→tank contents are throughly mixed

substrate load
MLVSS conc
oxygen demand

} uniform throughout the tank

→substrate conc. in the effluent is same as the substrate conc. in the reactor

→relatively simple to operate but to have low organic subs. conc. (i.e low F/M) that encourage the growth of filamentous bacteria causing sludge bulking

→ care should be taken to prevent short-circuiting of untreated or partially treated ww

(influent and effluent withdrawal points selection are important)

→ If shock loads or toxic discharges (large number of industrial connections) are a design consideration

a **complete mix reactor** can more easily withstand changing ww characteristics because the incoming ww is more or less uniformly dispersed with the reactor contents

→ Complete mix reactors are superior to plug flow reactors where wide fluctuations in flow rates occur

→however, in actual practice, a true plug flow regime is essentially impossible to obtain because of longitudinal dispersion caused by aeration & mixing

by dividing the aeration tank into a series f reactors (staged reactor desing) } process approaches plug flow kinetics with improved treatment efficiency compared to a complete mix process

Plug-Flow Activated Sludge Processes

→involves relatively long, narrow aeration basins, so that the concentration of soluble subtances and colloidal and suspended solids varies along the reactor length

→all particles entering the reactor stay in the reactor an equal amount of time

→substrate conc is continously varying of distance in the reactor

at the ifluent end →high readily degradable substrate

at the effluent end→ low readily degradable substrate

→where loading is reasonable constant, plug flow systems produce a more mature sludge with excellent settling characteristics

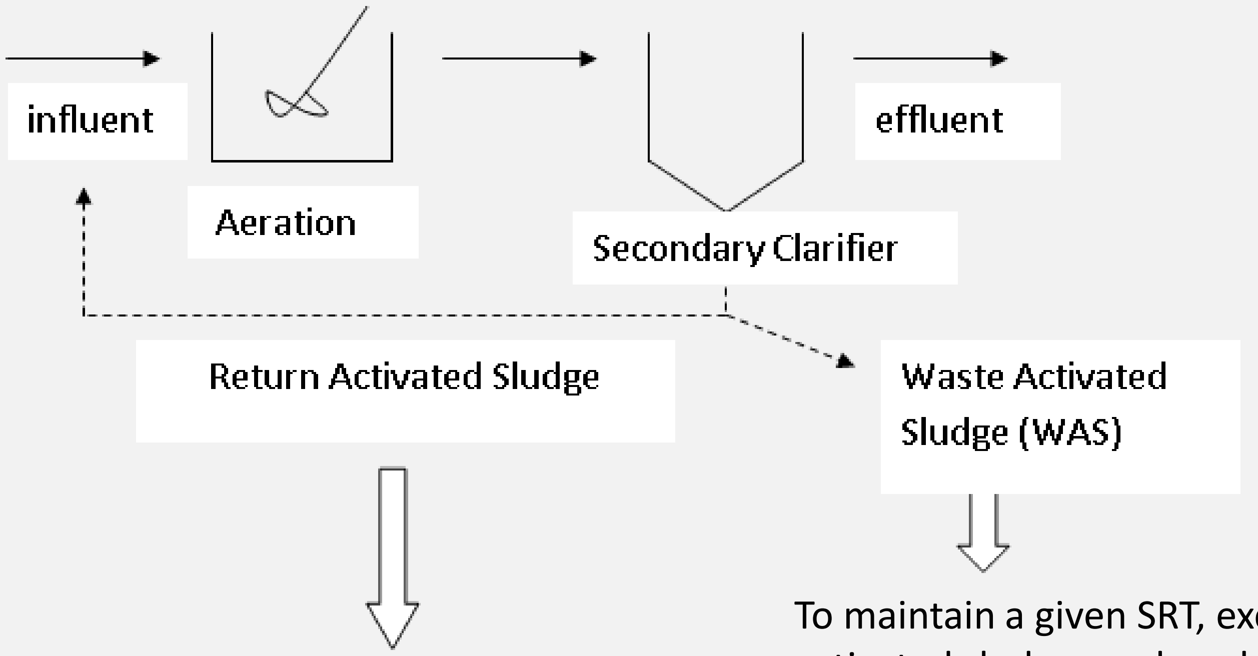
The true plug flow system is theoretically more efficient in the stabilization of most soluble wastes than in continous flow stirred tank reactors.

→In actual practice, a true plug flow regime is essentially impossible to obtain because of longitudinal dispersion caused by aeration & mixing

By dividing the aeration tank into a series of reactors (staged reactor design)	} Process approaches plug flow kinetics with improved treatment efficiency compared to a complete mix process

Biomass & Substrate Mass Balances in a Complete Mix Reactor

A) Wasting from the Sludge Return Line

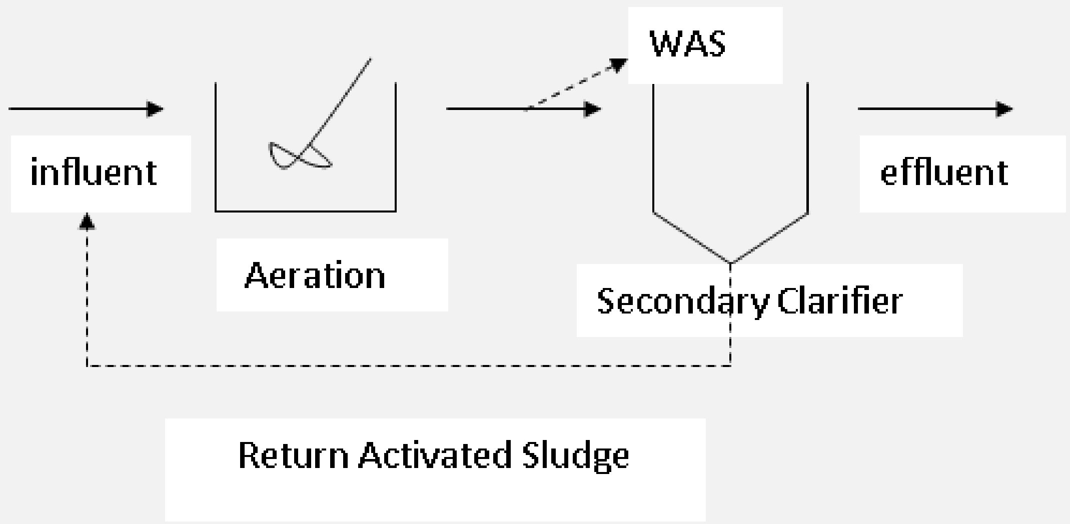


To maintain sufficient biomass concentration in aeration tank

To maintain a given SRT, excess activated sludge produced each day must be wasted

→ more concentrated sludge
→ requires small waste sludge pumps

B) Wasting from the Aeration Tank



→Withdrawal of mixed liquor (ww+biomass) directly from aeration tank

Less concentrated

→Good method if the process includes phosphorus removal

At the bottom of secondary clarifiers anaerobic conditions may develop → Release of phosphorus

Solids Retention Time (SRT) → mean cell residence time, sludge age , θ_c

The sludge or biomass requires a certain amount of time to assimilate the substrate and reproduce

If the sludge is not able to reproduce itself before being washed out of the system } failure will result

The ave period of time during which the sludge has remained in the aeration tank

SRT or θ_c

Residence time of sludge in the clarifier → does not contribute to the effective sludge age

no substrate in sec clarifier

low DO conc

metabolic activity of sludge is not significant

$$SRT(\theta_c) = \frac{\text{mass of organisms in the aeration tank}}{\text{mass of organisms removed daily}}$$

removal → wasting from RAS line or directly from aeration basin

removal → m.o overflowing the secondary clarifier weir into effluent (i.e. m.o. escaping from secondary clarifier)

→ The SRT (solids retention time) is completely anologous to HRT (hydraulic retention time)

However ; HRT and SRT are very different

(ϴ) HRT → is on the orders of hours

($ϴ_c$) SRT → is on the orders of days

} To achieve this, cells (microorganisms) are recyled from clarifier over and over again

For the case of aeration tank with no clarifier and thus no sludge recyle

$$\theta = \theta_C = \frac{VX}{QX}$$

→ SRT is the most critical paramater for activated – sludge design

It affects :

- treatment process performance
- aeration tank volume
- sludge production
- oxygen requirements

SRT_{min} ($\theta_{c\ min}$) → critical value

It is the residence time at which the cells are washed out or wasted from the system faster than they can reproduce

To ensure adequate waste treatment, biological treatment processes are usually designed and operated with $SRT = 2\text{-}20\ SRT_{min}$

Ref: Metcalf & Eddy

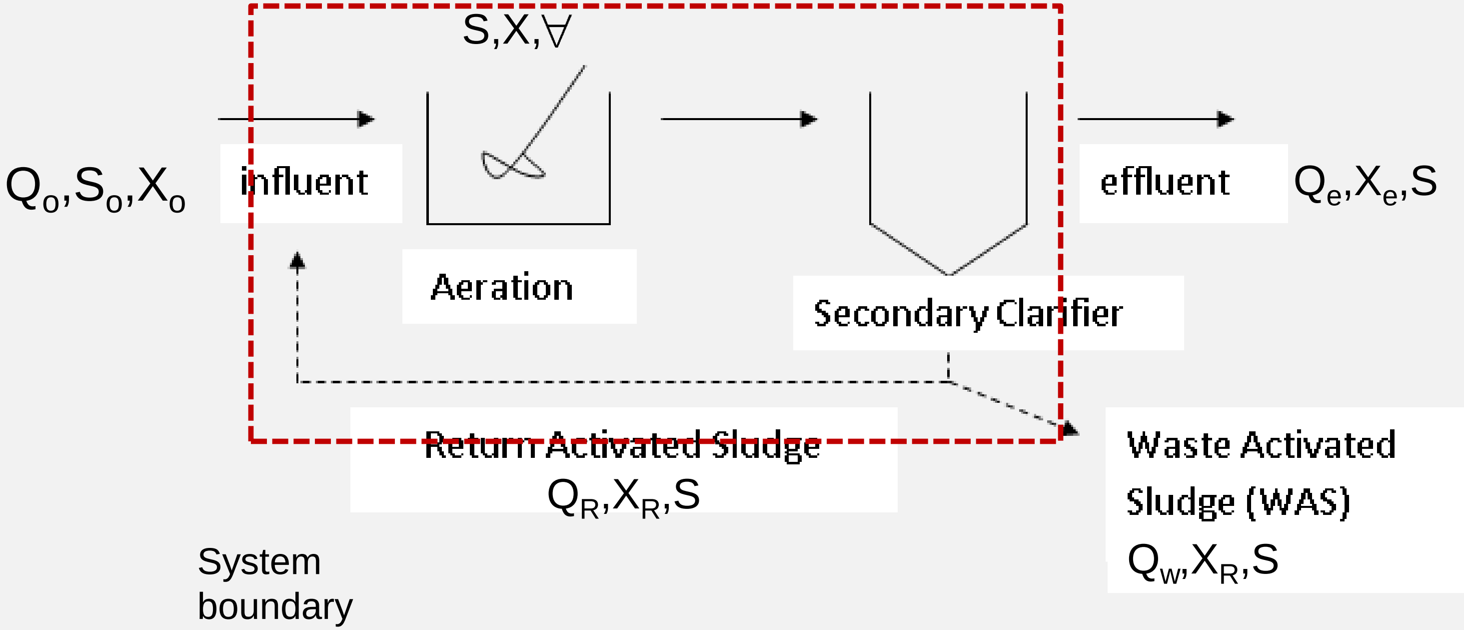
Table 8-6

Typical minimum SRT ranges for activated sludge treatment

Treatment goal	SRT Range, d	Factors affecting SRT
Removal of soluble BOD in domestic wastewater	1-2	Temperature
Conversion of particulate organics in domestic wastewater	2-4	Temperature
Develop flocculent biomassfor treating domestic wastewater	1-3	Temperature
Develop flocculent biomassfor treating industrial wastewater	3-5	Temperature/ compounds
Provide complete nitrification	3-18	Temperature/ compounds
Biological phosphorus removal	2-4	Temperature
Stabilization of activated sludge	20-40	Temperature
Degradation of xenobiotic compounds	5-50	Temperature/ specific bacteria/ compounds

* Adapted from Grady et al. (1999)

A) Mass Balance for the system including wasting from the Sludge Return Line



Biomass Mass Balance

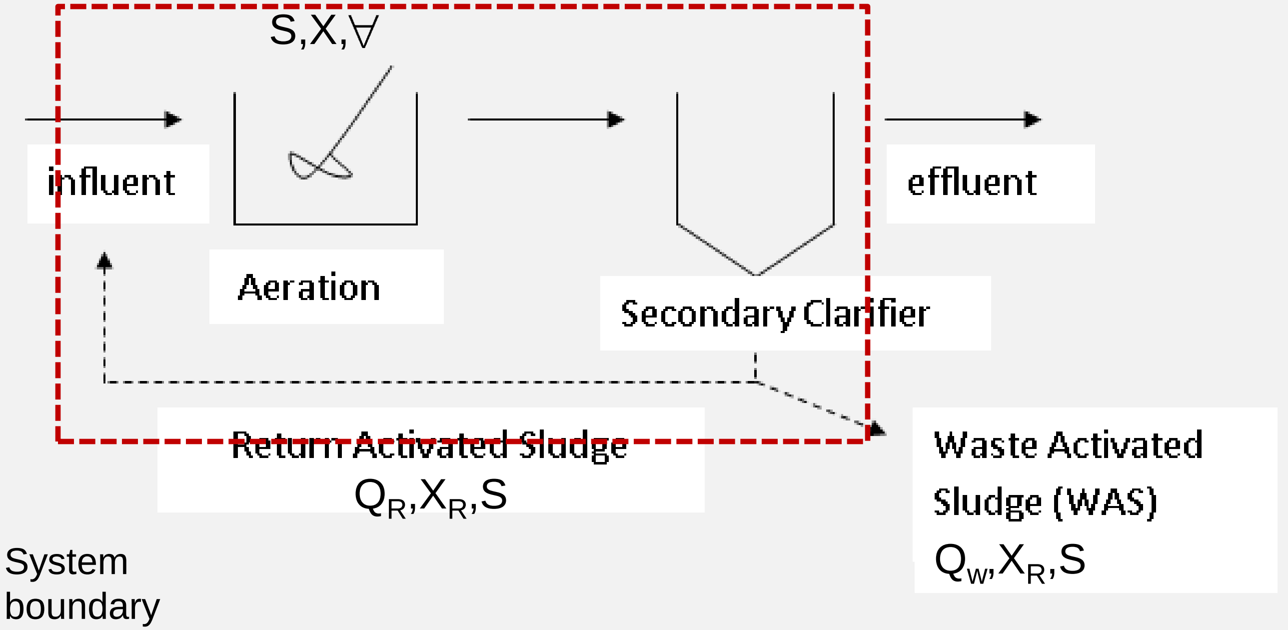
Accumulation = Inflow - Outflow + Generation

$$\frac{dX}{dt}\forall = QX_o - \left[(Q - Q_w)X_e + Q_w X_R\right] + r_g'\forall$$

$$\frac{dX}{dt}\forall = QX_o - \left[(Q - Q_w)X_e + Q_w X_R\right] + r_g'\forall$$

Assumption: 1) the conc. of m.o in the influent is negligible
2) steady-state conditions prevail

$$S = \text{effluent subst conc} = \frac{K_s(1 + k_d\theta_c)}{\theta_c(Yk - k_d) - 1}$$ $(Yk = \mu_m)$



Substrate Mass Balance

Accumulation = Inflow - Outflow + Generation

$$\frac{dS}{dt}\forall = QS_o - \left[Q_e S + Q_w S\right] + r_{su}\forall$$

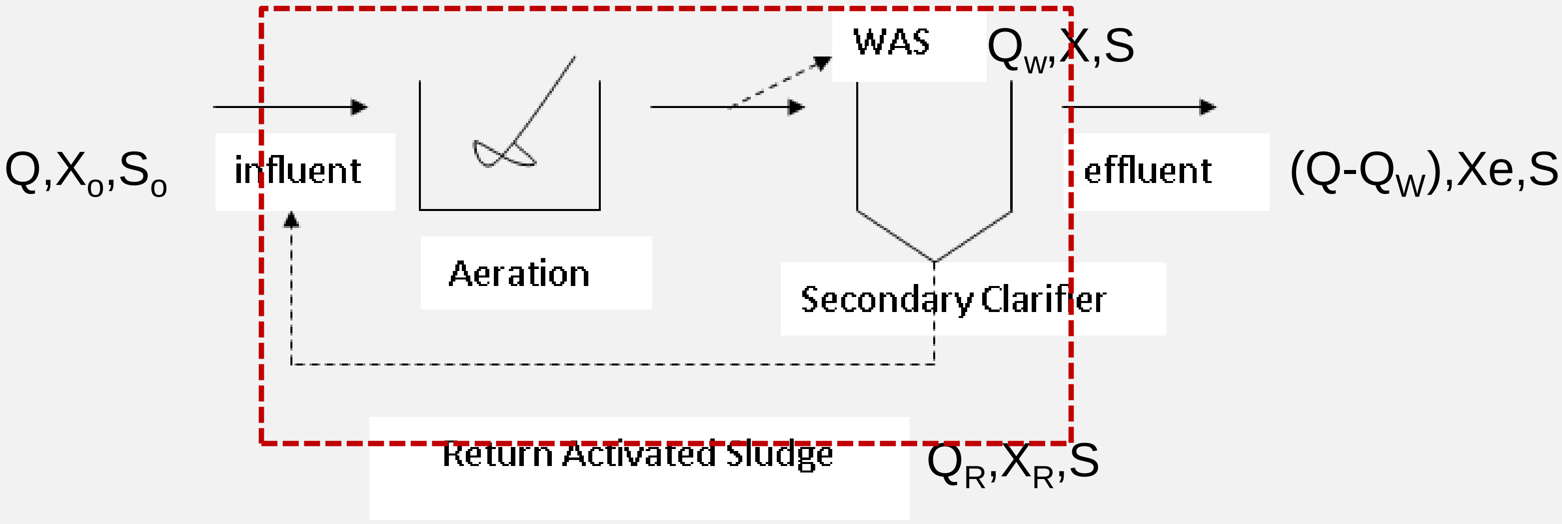
$$\frac{dS}{dt}\forall = QS_o - \left[Q_e S + Q_w S\right] + r_{su}\forall$$

Assumption: 1) the conc. of m.o in the influent is negligible

2) steady-state conditions prevail

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

B) Mass Balance for the system including wasting from the aeration tank



Biomass Mass Balance

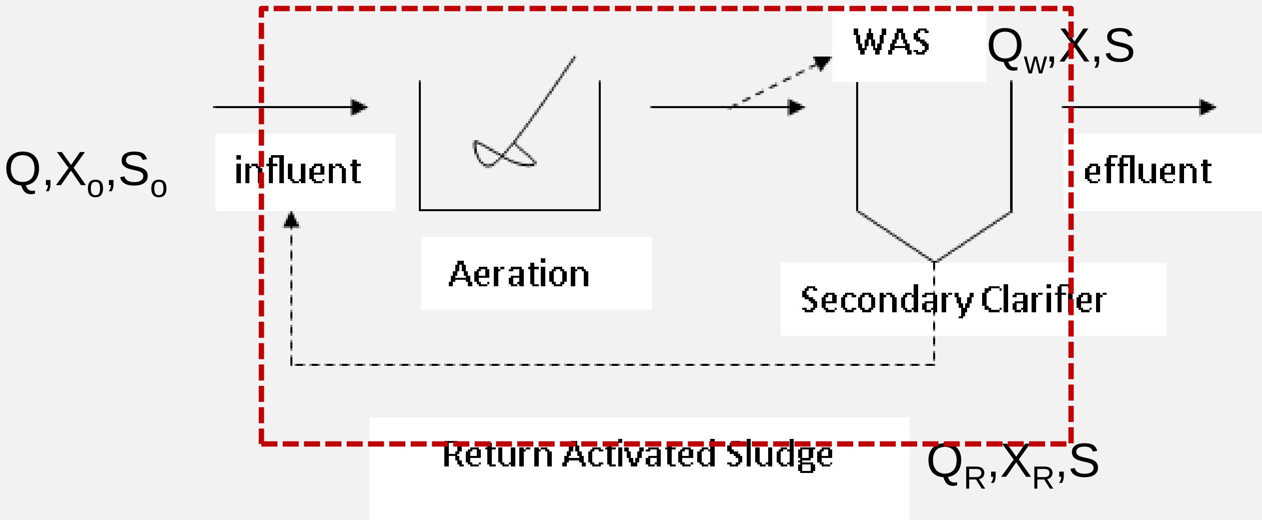
Accumulation = Inflow - Outflow + Generation

$$\frac{dX}{dt}\forall = QX_o - \left[(Q - Q_w)X_e + Q_w X\right] + r_g' \forall$$

$$\frac{dX}{dt}\forall = QX_o - \left[(Q - Q_w) X_e + Q_w X \right] + r_g' \forall$$

Assumption: 1) the conc. of m.o in the influent is negligible
2) steady-state conditions prevail

$$S = \text{eff. subst. conc.} = \frac{K_s (1 + k_d \theta_c)}{\theta_c (Yk - k_d) - 1}$$



Substrate Mass Balance

Accumulation = Inflow - Outflow + Generation

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Accumulation = Inflow - Outflow + Generation

$$\frac{dS}{dt}\forall = QS_o - \left[Q_e S + Q_w S\right] + r_{su}\forall$$

Assumption: 1) the conc. of m.o in the influent is negligible
2) steady-state conditions prevail

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

Solids Production

Total MLVSS conc in the aeration tank, X_T = biomass conc + non – biodegradable VSS conc

biomass conc: X

non – biodegradable VSS conc: X_i

- nbVSS from cell debris
- nbVSS in the influent

$$\text{Biomass conc}\,(X, g/m^3) = \frac{\theta_c}{\theta}\left[\frac{Y(S_o - S)}{1 + k_d\theta_c}\right]$$ (from substrate mass balance)

nbVSS from cell debris (g/m^3) = $F_d\, k_d\, X\, \theta_c$

$$= F_d k_d \left[\frac{\theta_c}{\theta}\left(\frac{Y(S_o - S)}{1 + k_d\theta_c}\right)\right]\theta_c$$

$$n\text{bVSS in the influent}\,(g/m^3) = \frac{QX_{o,i}}{\forall}\theta_c = \frac{X_{o,i}\theta_c}{\theta}$$

$$X_T = \frac{\theta_C}{\theta}\left[\frac{Y(S_o - S)}{1 + k_d\theta_c}\right] + F_d k_d \left[\frac{\theta_c}{\theta}\left(\frac{Y(S_o - S)}{1 + k_d\theta_c}\right)\right]\theta_c + \frac{X_{o,i}\theta_C}{\theta}$$

$$\text{Sludge age} = \theta_c = \frac{\text{mass of solids in the aeration tank}}{\text{mass of solids wasted per day}} = \frac{\forall X_T}{P_{X_T,VSS}}$$

$$P_{X_T,VSS} = \frac{\forall\left\{\frac{\theta_c}{\theta}\left[\frac{Y(S_o - S)}{1 + k_d\theta_C}\right] + F_d k_d\left[\frac{\theta_C}{\theta}\left(\frac{Y(S_o - S)}{1 + k_d\theta_C}\right)\right]\theta_C + \frac{X_{o,i}\theta_C}{\theta}\right\}}{\theta_C}$$

$$P_{X_T,VSS} = \forall\left[\frac{Y(S_o - S)}{\theta(1 + k_d\theta_C)}\right] + F_d k_d \frac{Y(S_o - S)}{\theta(1 + k_d\theta_C)}\theta_C + \frac{X_{o,i}}{\theta}$$

$$P_{X_T,VSS} = \frac{QY(S_o - S)}{(1 + k_d\theta_c)} + F_d k_d Y \frac{Q(S_o - S)\theta_C}{(1 + k_d\theta_c)} + X_{o,i}Q$$

$$P_{X_T,VSS} = \frac{QY(S_o - S)}{(1 + k_d\theta_c)} + F_d k_d Y \frac{Q(S_o - S)\theta_C}{(1 + k_d\theta_c)} + X_{o,i}Q$$

$$P_{X_T,TSS} = \frac{\frac{QY(S_o - S)}{(1 + k_d\theta_c)}}{VSS/TSS} + \frac{F_d k_d Y \frac{Q(S_o - S)\theta_C}{(1 + k_d\theta_c)}}{VSS/TSS} + X_{o,i}Q + Q(TSS_0 - VSS_0)$$

$$\theta_C = \frac{VX_{TSS}}{P_{X_T,TSS}} = \frac{VX_{VSS}}{P_{X_T,VSS}}$$

A_s θ_C $\uparrow$ more biomass decays more cell debris accumulates $\longrightarrow$ the difference bw MLVSS and biomass VSS conc increases

The Observed Yield (Y_{obs})

$$Y_{obs} = \frac{\text{amount of solids production measured}}{\text{amount of substrate removal measured}}$$

$$Y_{obs} = \frac{\frac{QY(S_o - S)}{1 + k_d\theta_c} + F_d k_d \frac{YQ(S_o - S)\theta_c}{1 + k_d\theta_c} + X_{o,i}Q}{Q(S_o - S)}$$

→decreases as the θc ↑ due to biomass loss by more endogenous respiration

→lower with increasing temp as a result of a higher endogenous resp. rate at higher temp.

→higher when no primary treatment is used, as more nbVSS remains in the influent ww.

$$Y_{obs} = \frac{\frac{QY(S_o - S)}{1 + k_d\theta_c} + F_d k_d \frac{YQ(S_o - S)\theta_c}{1 + k_d\theta_c} + X_{o,i}Q}{Q(S_o - S)}$$

$$Y_{obs} = \frac{Y}{1 + k_d\theta_c} + \frac{f_d k_d Y\theta_c}{1 + k_d\theta_c} + \frac{X_{o,i}}{S_o - S}$$

→ depends on ww characteristics & type of pretreatment $S << S_o$

Biomass cell debris influent nbVSS conc.

$$\frac{X_{o,i}}{S_o} = 0.1 - 0.3 \text{ with primary treatment}$$

$$= 0.3\text{-}0.5 \text{ without primary treatment}$$

$$P_{X_T,VSS} = QY_{obs}(S_o - S)$$

F/M (Food / Microorganism) Ratio

$$\frac{F}{M} = \frac{\text{total applied substraterate}}{\text{total microbial biomass}} = \frac{QS_o}{\forall X}$$

Q → influent flowrate (m^3/d)

S_o → influent BOD or bsCOD conc (g/m^3)

X → mixed liquor biomass conc. in the aeration tank (g/m^3)

$\forall$ → aeration tank volume (m^3)

$$U = \text{specific substrate utilization rate} = \frac{r_{su}}{X} = \frac{(S_o - S)/\theta}{X} = \frac{S_o - S}{\theta X}$$

$$E = \text{process BOD or bsCOD removal eff \%} = \frac{S_0 - S}{S_0} 100$$

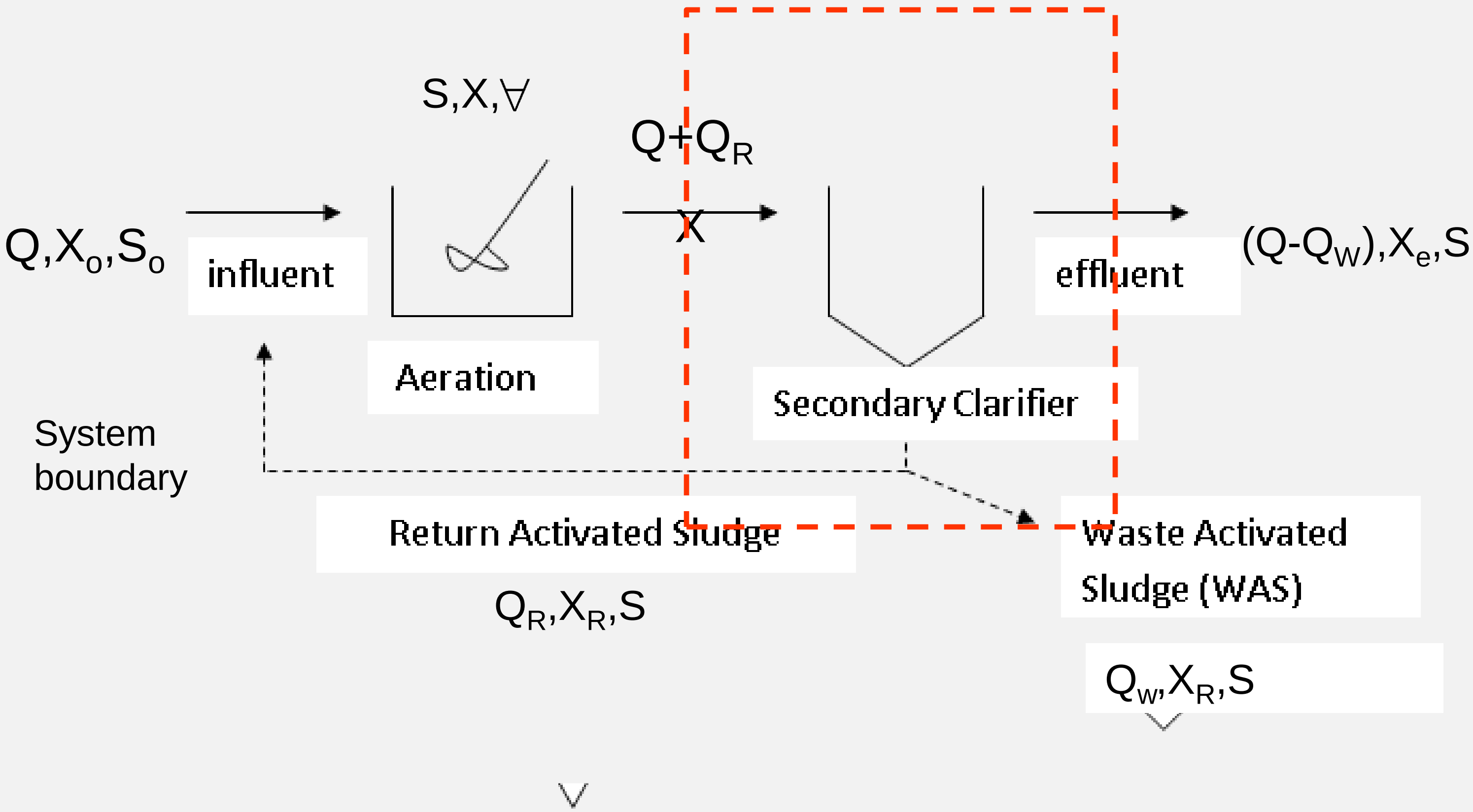
$$\frac{U}{E} = \frac{\frac{S_o - S}{\theta X}}{\frac{S_o - S}{S_o}100} = \frac{S_o}{\theta X(100)} = \frac{QS_o}{\forall X100} \longrightarrow \frac{U}{E} = \frac{F/M}{100} \longrightarrow \boxed{U = \frac{(F/M)E}{100}}$$

F/M → 0.1 – 0.05 g BOD/ g VSS.d (for Θ_C=20 – 30 d)

→ 0.3 – 0.5 g BOD/g VSS.d (for Θ_C=5 – 7 d)

Return Sludge Pumping Rate

A) Wasting from the Secondary Clarifier



Biomass Mass Balance around secondary clarifier

Accumulation = Inflow - Outflow + Generation

$$\frac{dX}{dt}\forall = (Q+Q_r)X - \left[Q_e X_e + Q_w X_r + Q_r X_R\right]$$

Assumption: 1) steady-state conditions prevail

2) solids in the effluent from the settling tank is negligible

$$\frac{dx}{dt}=0=\frac{Q+Q_R}{\forall}X-\left[\frac{Q_eX_e+Q_wX_R+Q_RX_R}{\forall}\right]$$

$$\frac{QX+Q_RX}{\forall}=\frac{Q_WX_R}{\forall}+\frac{Q_RX_R}{\forall}$$

$$\theta_c=\frac{\forall X}{(Q-Q_w)X_e+Q_wX_R}\cong\frac{\forall X}{Q_wX_R}$$

(for wasting from RAS)

$$\frac{Q_wX_R}{\forall}=\frac{X}{\theta_c}$$

$$\frac{QX+Q_RX}{\forall}=\frac{X}{\theta_c}+\frac{Q_RX_R}{\forall}$$

$$\frac{QX}{\forall} - \frac{X}{\theta_c} = \frac{Q_R X_R}{\forall} - \frac{Q_R X}{\forall}$$

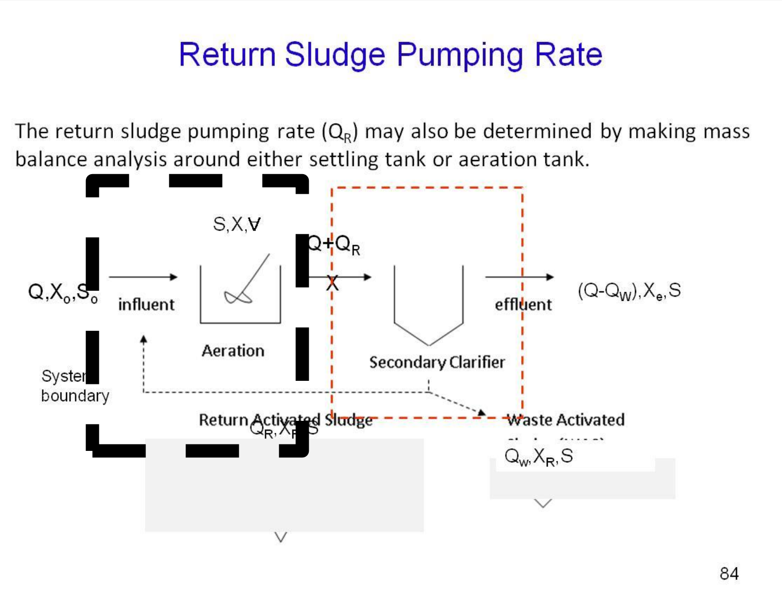
$$\frac{\left(\frac{QX}{\forall} - \frac{X}{\theta_C}\right)\forall}{\left(X_R - X\right)} = Q_R$$

$$\boxed{Q_R = \frac{XQ - \frac{X\forall}{\theta_C}}{X_R - X}} \longrightarrow Q_R = \frac{X\left(Q - \frac{Q\theta}{\theta_C}\right)}{X_R - X}$$

$$R = \frac{Q_R}{Q} = \frac{\left(\frac{XQ\left(1 - \frac{\theta}{\theta_C}\right)}{X\left(\frac{X_R}{X} - 1\right)}\right)}{Q}$$

$$\boxed{R = \frac{Q_R}{Q} = \frac{1 - \left(\theta / \theta_C\right)}{\left(X_R / X\right) - 1}}$$

If you write **biomass mass balance around aeration tank**
(boundary cond : black dotted line)



Accumulation = Inflow - Outflow

$$\frac{dx}{dt}\forall = (QX_0 + Q_R X_R) - (Q + Q_R)X$$

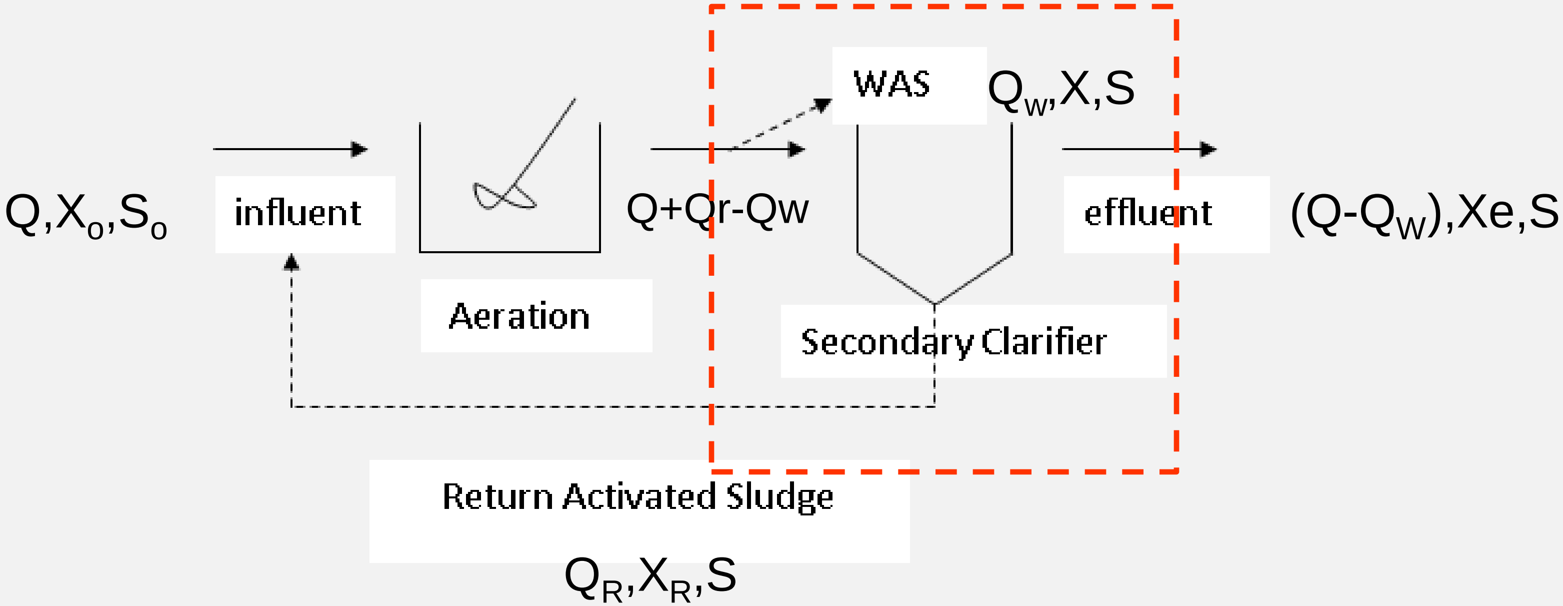
Assumptions: 1) steady-state conditions prevail
2) X_0 is negligible
3) new cell growth is negligible

$$0 = \frac{Q_R X_R}{\forall} - \frac{QX}{\forall} - \frac{Q_R X}{\forall}$$

$$\frac{QX}{\forall} = \frac{Q_R (X_R - X)}{\forall}$$

$$R = \frac{Q_R}{Q} = \frac{X}{X_R - X}$$

B) Wasting from the Aeration Tank



Biomass Mass Balance

Accumulation = Inflow - Outflow + Generation

$$\frac{dX}{dt}\forall = \left[(Q + Q_R - Q_w)X - (Q_e X_e + Q_R X_R)\right]$$

Assumptions: 1)solids in the eff from the settling tank is negligible

2) steady-state conditions prevail

$$\frac{dx}{dt} = 0 = \frac{(Q + Q_R - Q_w)X}{\forall} - \frac{Q_e Xe + Q_R X_r}{\forall}$$

$$0 = \frac{QX + Q_R X - Q_W X - Q_R X_R}{\forall}$$

$$\frac{Q_W X}{\forall} = \frac{QX + Q_R (X - X_R)}{\forall}$$

$$\frac{X}{\theta_C} = \frac{QX + Q_R (X - X_R)}{\forall}$$

$$Q_R = \left(\frac{\forall X}{\theta_C} - QX\right) \Big/ (X - X_R)$$

$$Q_R = \frac{QX - \frac{X\forall}{\theta_C}}{X_R - X}$$

Recyle ratio= $R = \frac{Q_R}{Q} = \frac{1 - (\theta/\theta_C)}{(X_R/X) - 1}$

Determination of Biomass Conc. in the Return Sludge (X_R)

SVI (Sludge Volume Index) → settleability test method often used to control the rate of return sludge pumping

SVI → Volume occupied by 1g of sludge after 30 min of settling

- Mixed-liquor sample is placed in a 1 to 2-L cylinder
- MLSS conc. of the sample is determined
- Settled volume after 30 min is measured

$$SVI = \frac{\text{settled volume of sludge ml/L}}{\text{suspended solids mg/L}} = \frac{\text{ml}}{\text{g}}$$

SVI ≈ 100 ml/g → considered a good settling sludge

SVI>150 ml/g → associated with filementous growth → sludge bulking problem

Example: A mixed – liquor sample with a 3000mg/L TSS conc settles to a volume of 300mL in 30 min in a 1 L cylinder SVI=?

$$SVI = \frac{300\ ml/L}{3000\ mg/L} = 0.1\frac{ml}{mg}\frac{1000\ mg}{g} = 100\frac{ml}{g}$$

$$\rightarrow X_R = \frac{g}{ml}\frac{1000\ ml}{1L}\frac{1000\ mg}{1g}$$

$$SVI = \frac{ml}{g} \rightarrow \frac{1}{SVI} = \frac{g}{ml} = X_R$$

$$\rightarrow X_R = \frac{10^6}{SVI}$$

In ATV approach,

$$X_R = \frac{10^6 2^{1/3}}{SVI}$$

$$X_R = \frac{10^6}{SVI} \Rightarrow X_R = \frac{10^6}{100} = 10000\ mg/L$$

$$R = \frac{Q_R}{Q} = \frac{X}{X_R - X} = \frac{3000}{10000 - 3000} = 0.43$$

Ref: Metcalf & Eddy

Table 8–5
Summary of equations used in the analysis of suspended growth processes

Equation	Eq. No.
$k_T = k_{20}\theta^{(T-20)}$	2–25
$r_{su} = -\dfrac{kXS}{K_s + S}$	7–12
$\mu_m = kY$	7–13
$r_{su} = -\dfrac{\mu_m XS}{Y(K_s + S)}$	7–15
$r_g = Y\dfrac{kXS}{K_s + S} - k_d X$	7–22
$\mu = \dfrac{r_g}{X}$	7–23
$\mathrm{SRT} = \dfrac{VX}{(Q - Q_w)X_e + Q_w X_R}$	7–35
$\mathrm{SRT} = \dfrac{1}{\mu}$	7–37
$\dfrac{1}{\mathrm{SRT}} = -\dfrac{YkS}{K_s + S} - k_d$	7–39
$S = \dfrac{K_s[1 + (k_d)\mathrm{SRT}]}{\mathrm{SRT}(Yk - k_d) - 1}$	7–40
$X = \left(\dfrac{\mathrm{SRT}}{\tau}\right)\left[\dfrac{Y(S_o - S)}{1 + (k_d)\mathrm{SRT}}\right]$	7–43
$(X_{VSS})(V) = (P_{X,VSS})\mathrm{SRT}$	7–54
$(X_{TSS})(V) = (P_{X,TSS})\mathrm{SRT}$	7–55
$R_o = Q(S_o - S) - 1.42\,P_{X,bio}$	7–59
$F/M = \dfrac{QS_o}{VX}$	7–60
$L_{org} = \dfrac{(Q)(S_o)}{(V)}$	7–67
$\mathrm{SF} = \mathrm{SRT}_{des}/\mathrm{SRT}_{min}$	7–71
$\mu_n = \left(\dfrac{\mu_{nm} N}{K_n + N}\right)\left(\dfrac{\mathrm{DO}}{K_o + \mathrm{DO}}\right) - k_{dn}$	7–93
$r_{su} = -\left(\dfrac{kXS}{K_s + S}\right)\left(\dfrac{\mathrm{NO_3}}{K_{s,NO_3} + \mathrm{NO_3}}\right)\left(\dfrac{K'_o}{K'_o + \mathrm{DO}}\right)\eta$	7–110

Definition of terms	
DO	= dissolved oxygen, ML^{-3}
F/M	= food to microorganism ratio
k	= maximum rate of substrate utilization, T^{-1}
k_d	= endogenous decay coefficient, T^{-1}
k_{dn}	= endogenous decay coefficient for nitrifying organisms, T^{-1}
k_T	= reaction rate coefficient at temperature (T)
k_{20}	= reaction rate coefficient at 20°C
K_n	= half-velocity constant, ML^{-3}
K'_o	= oxygen inhibition coefficient, ML^{-3}
K_s	= half-velocity constant, ML^{-3}
K_{s,NO_3}	= half-velocity constant for nitrate limited reaction, ML^{-3}
L_{org}	= volumetric organic loading rate, $ML^{-3}T^{-1}$
μ	= specific growth rate, T^{-1}
μ_m	= maximum specific growth rate, T^{-1}
μ_n	= specific growth rate for nitrification, T^{-1}
μ_{nm}	= maximum specific growth rate of nitrifying bacteria, T^{-1}
N	= nitrogen concentration, ML^{-3}
η	= ratio of substrate utilization rate with nitrate versus oxygen as the electron acceptor
P_X	= solids, MT^{-1}
Q	= flowrate, L^3T^{-1}
Q_w	= waste sludge flowrate L^3T^{-1}
R_o	= oxygen, MT^{-1}
r_g	= net biomass production rate, $ML^{-3}T^{-1}$
r_{su}	= soluble substrate utilization rate, $ML^{-3}T^{-1}$
S	= concentration of growth-limiting substrate in solution, ML^{-3}
SF	= safety factor
S_o	= influent concentration, ML^{-3}
SRT	= solids retention time, T
TSS	= total suspended solids, M
τ	= hydraulic retention time (V/Q), T
θ	= temperature activity coefficient
U	= substrate utilization rate, T^{-1}
V	= volume, L^3
VSS	= volatile suspended solids, M
X	= biomass concentration, ML^{-3}
X_e	= concentration of biomass in the effluent, ML^{-3}
X_R	= concentration of biomass in the return line from clarifier, ML^{-3}
Y	= biomass yield, M of cell formed per M of substrate consumed

Note: Expressions for units are M = mass, L = length, and T = time.