Aalto University
School of Engineering

Modelling and Control of Water and wastewater treatment processes

WAT - E2130

Lecture 3 Influent fractions and nutrient removal
Modelling physical and chemical processes

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Lecture outline

SUMO EXAM

INFLUENT FRACTIONS

Wastewater and biomass fractions

Role of different fractions in models

NUTRIENT REMOVAL

Nitrogen removal

Phosphorus removal

Anaerobic digestion

EXERCISE WITH SUMO

HW2 Exercise 1

MODELLING PHYSICAL PROCESSES

Phase separation

Mixing

MODELLING CHEMICAL PROCESSES

pH

Chemical phosphorus removal

EXERCISE WITH SUMO

HW2 Exercise 4

Klaukkala WWTP excursion & individual project work

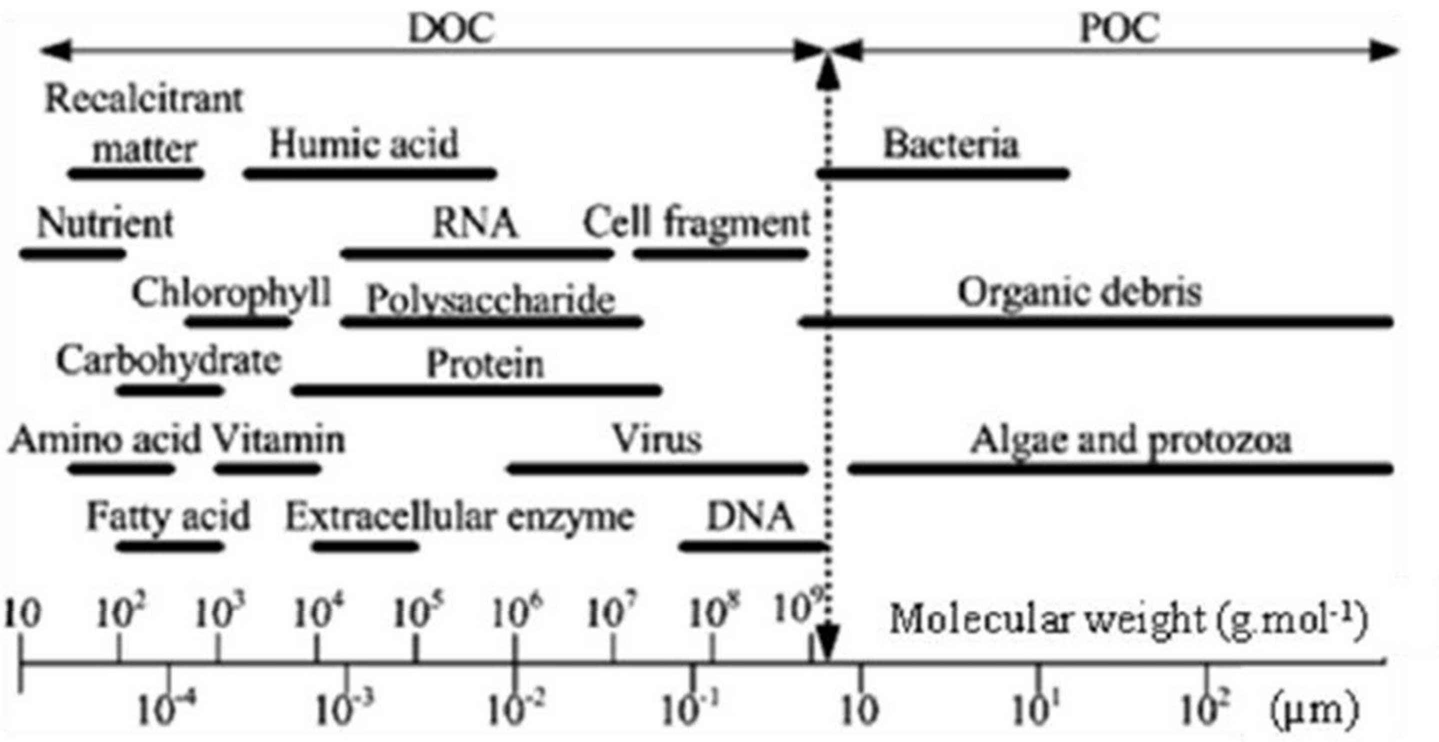
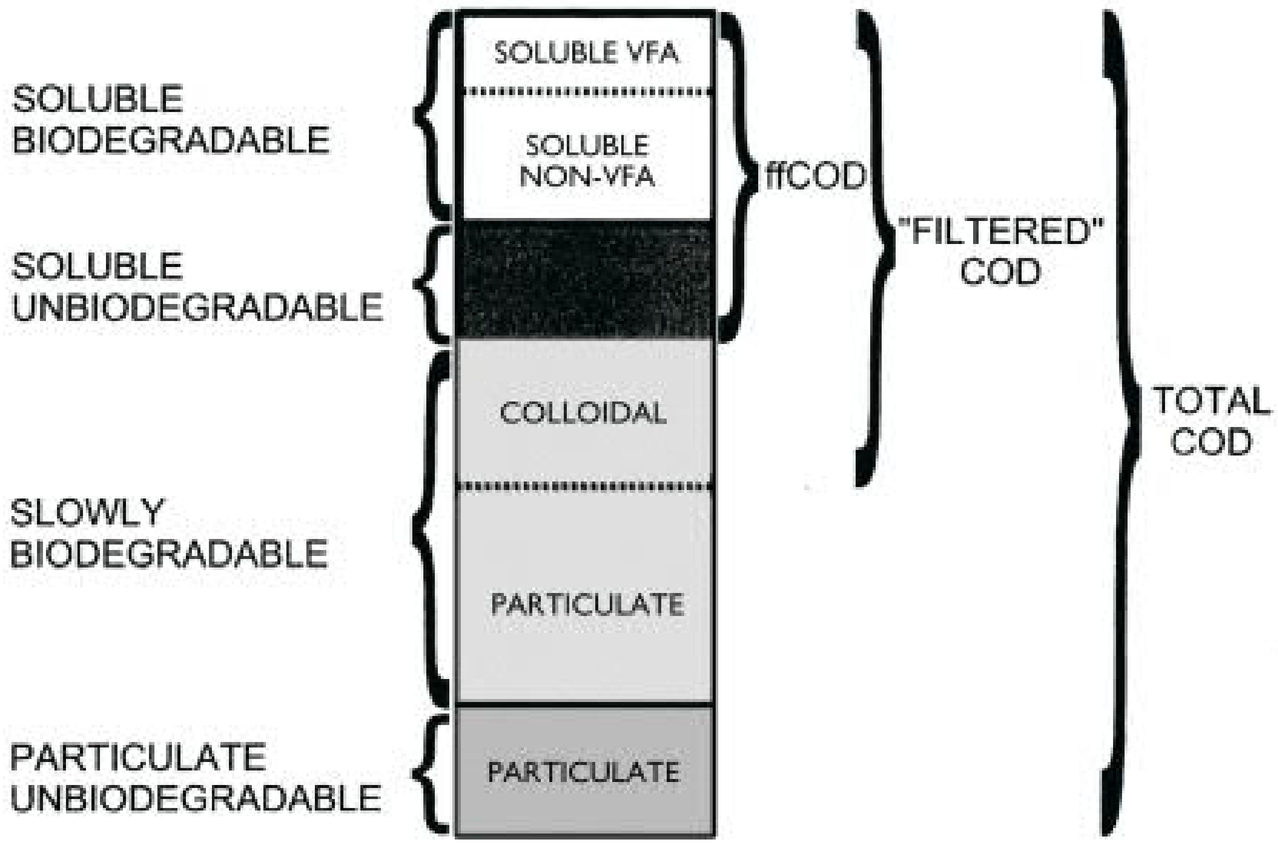
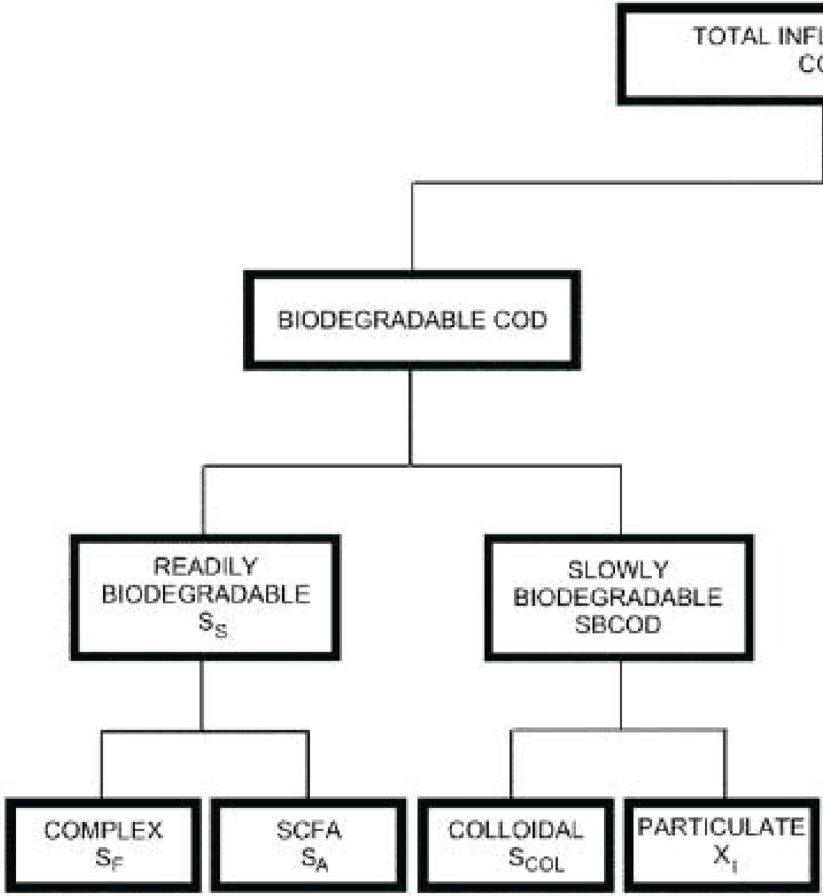


Figure 1: Organic Components in Traditional Wastewater Treatment Plant Effluent. Adapted from Shon et al. (2006).

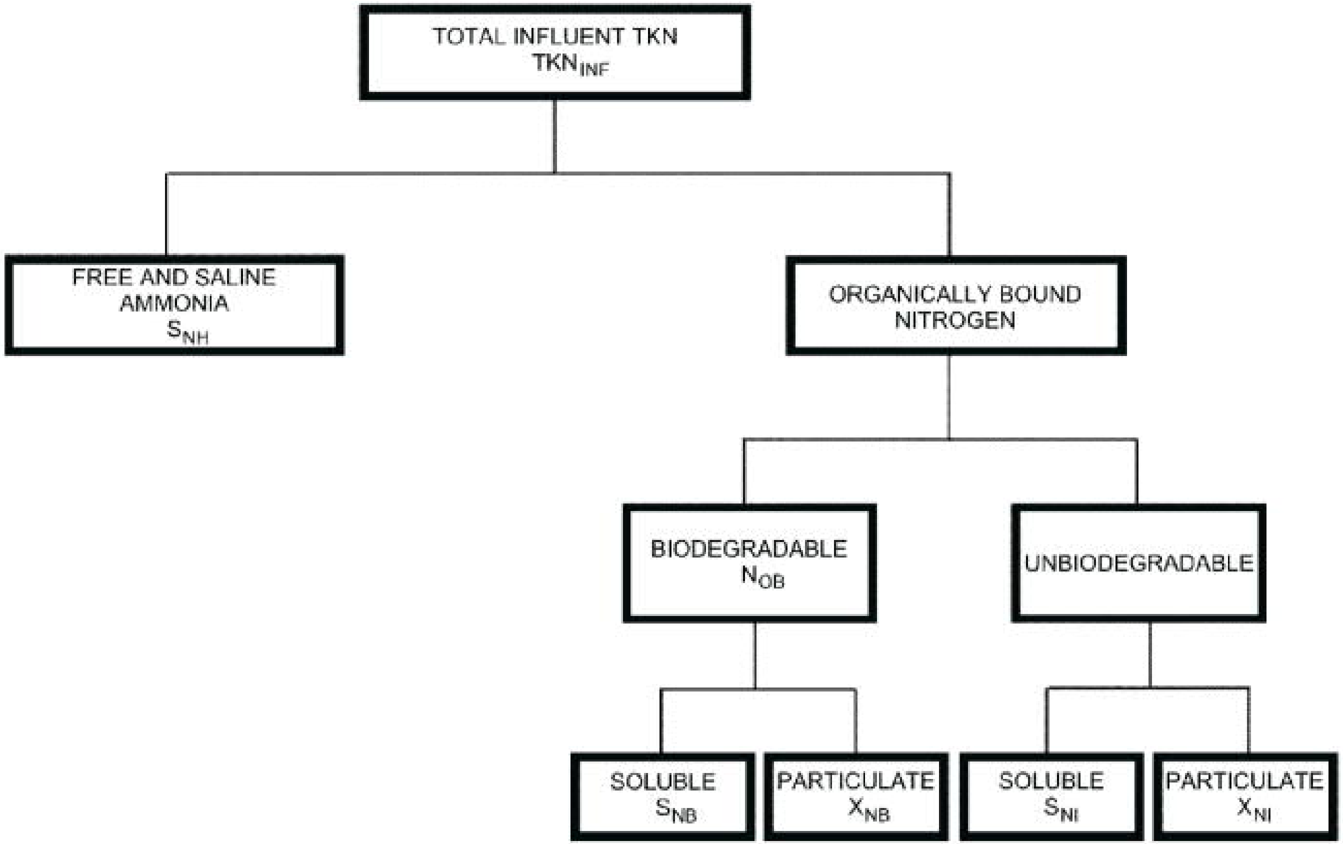
Fractionation of COD



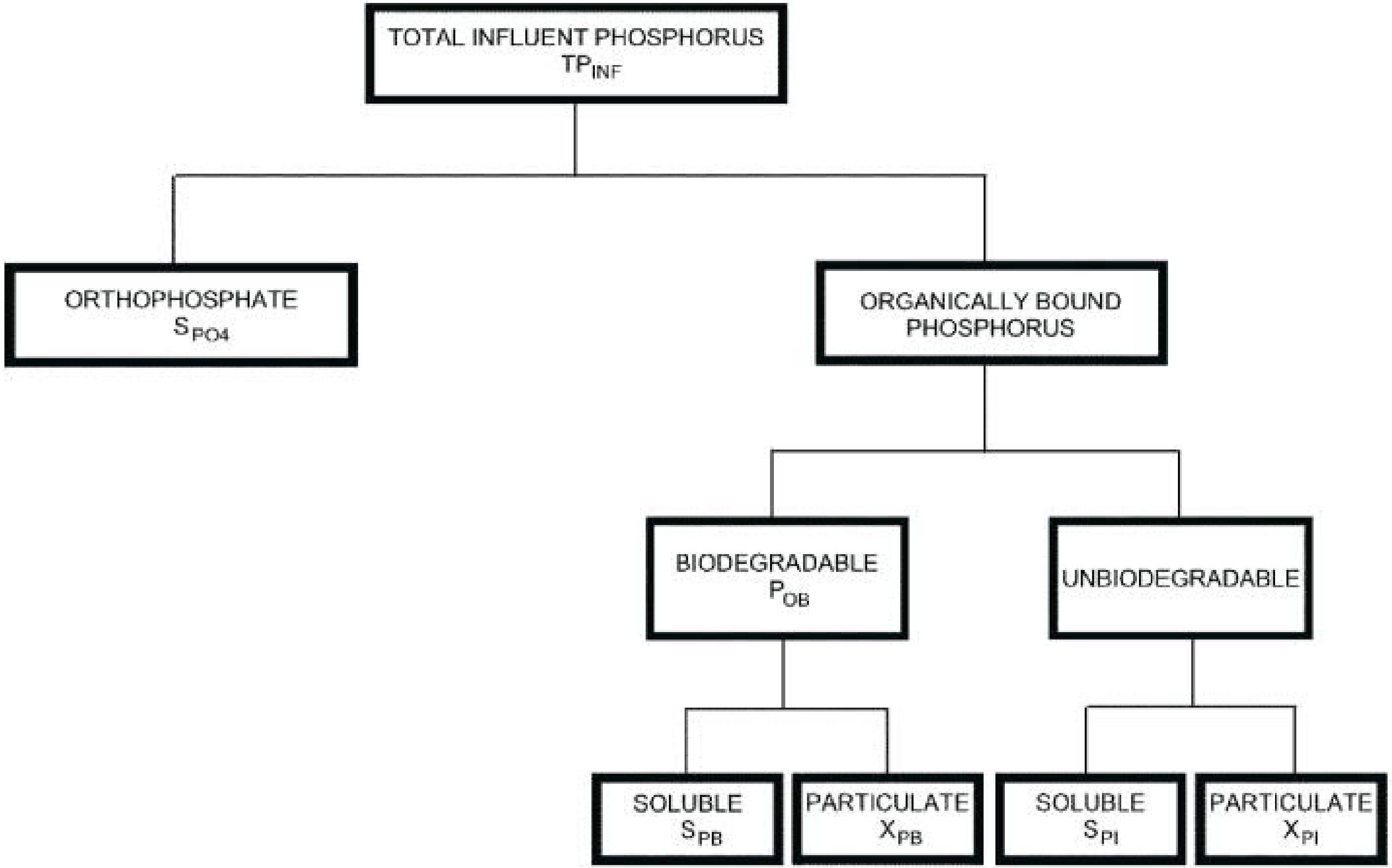
Organic matter



Nitrogen


TOTAL INFLUENT TKN
TKN_{INF}
FREE AND SALINE AMMONIA
S_{NH}
ORGANICALLY BOUND NITROGEN
BIODEGRADABLE
N_{OB}
UNBIODEGRADABLE
SOLUBLE
S_{NB}
PARTICULATE
X_{NB}
SOLUBLE
S_{NI}
PARTICULATE
X_{NI}

Phophorus


TOTAL INFLUENT PHOSPHORUS
TP_{INF}
ORTHOPHOSPHATE
S_{PO4}
ORGANICALLY BOUND PHOSPHORUS
BIODEGRADABLE
P_{OB}
UNBIODEGRADABLE
SOLUBLE
S_{PB}
PARTICULATE
X_{PB}
SOLUBLE
S_{PI}
PARTICULATE
X_{PI}

Why is influent quality important?

- **Readily biodegradable organic matter**
  - Oxygen demand pattern
  - Determines process’s ability to enhanced biological P removal
  - Is denitrification achieved with wastewater’s own carbon source
- **Unbioderadable particulate COD**
  - Affects the oxygen demand
  - Affects the sludge yield

- **Influent quality also affects e.g. the performance of the primary clarifier**
- **Biggest differences with industrial wastewater**

Influent COD fractionation

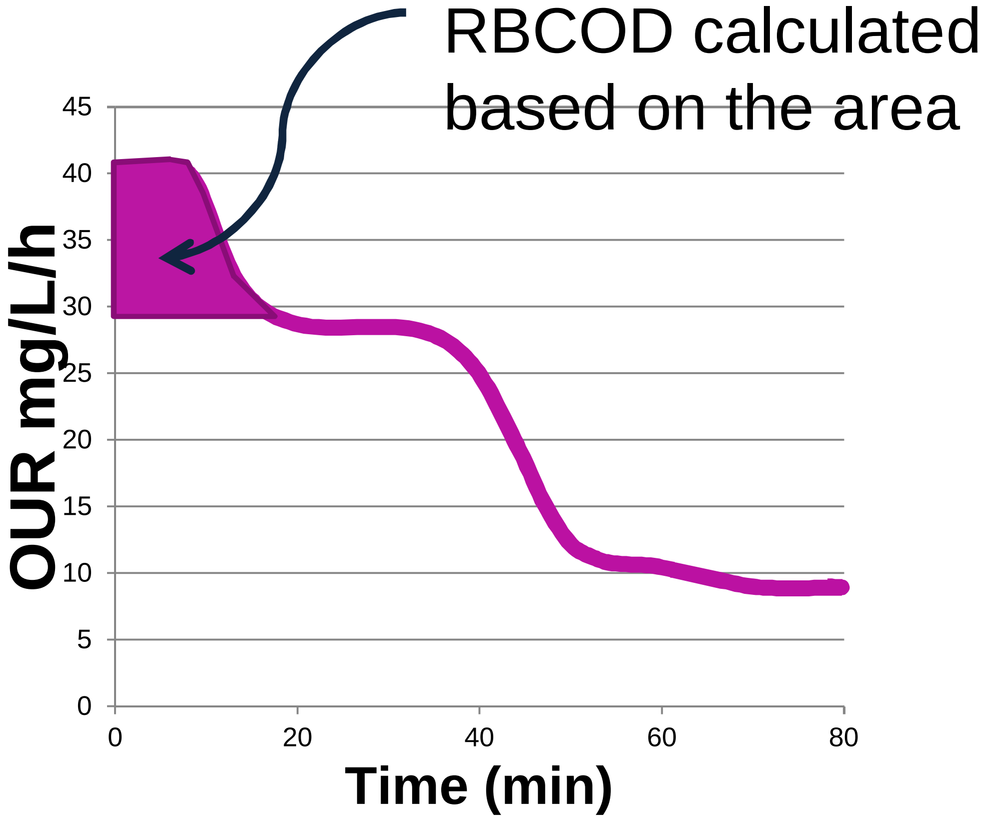
- **TCOD** = $X_B + X_U + C_B + C_U + S_B + S_U$

  ($X_B + X_U$: Particulate; $C_B + C_U$: Colloidal; $S_B + S_U$: Soluble)

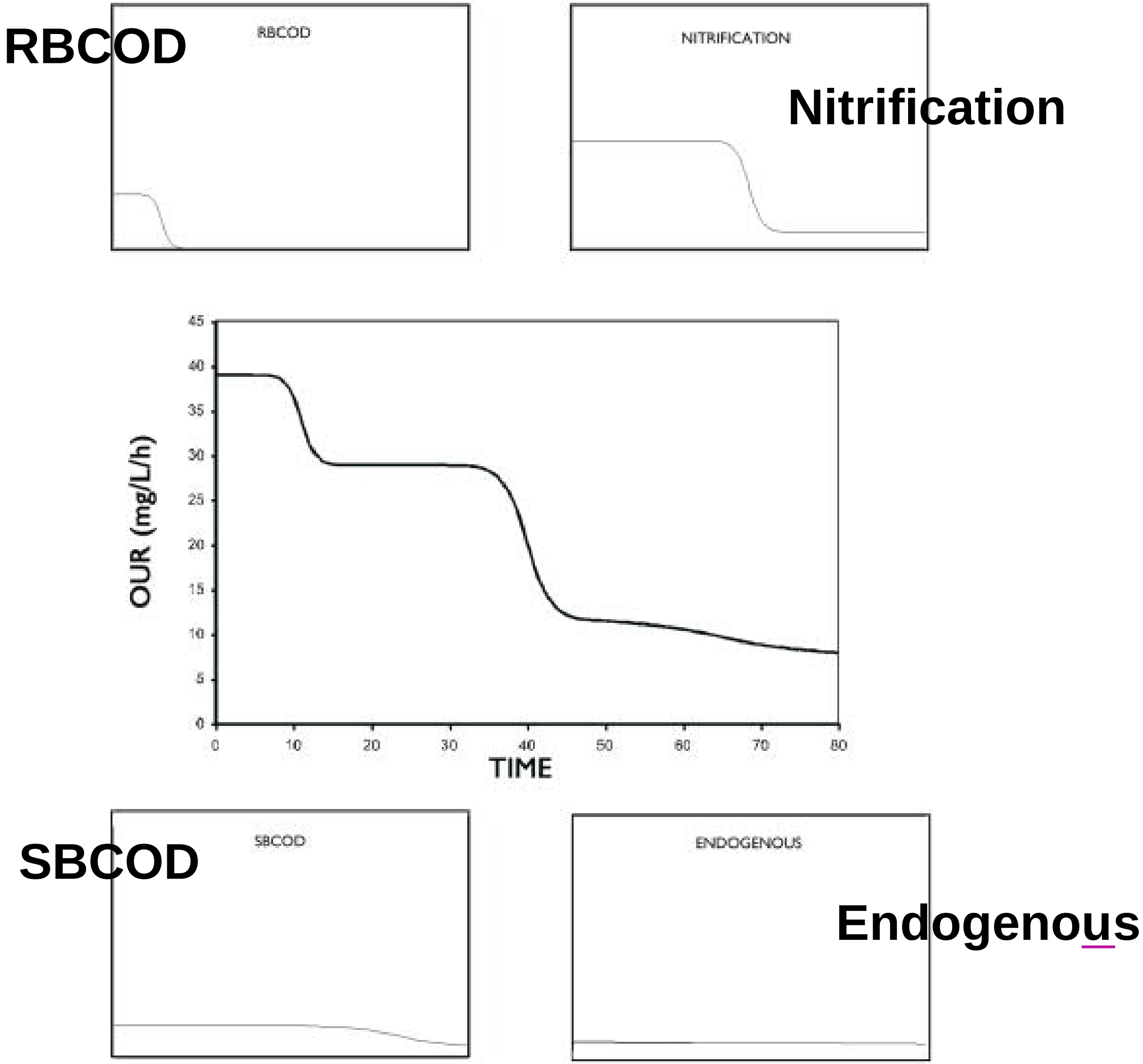
- $\mathbf{FCOD_{1.2\mu m}} = C_B + C_U + S_B + S_U$
- **ffCOD** = $S_B + S_U$ ($ZnSO_4$ at 10 pH using NaOH)
- **RBCOD** = $ffCOD_{Influent} - ffCOD_{Final\ effluent}$
- **OUR** for OHO determination

RBCOD measurement by respirometry

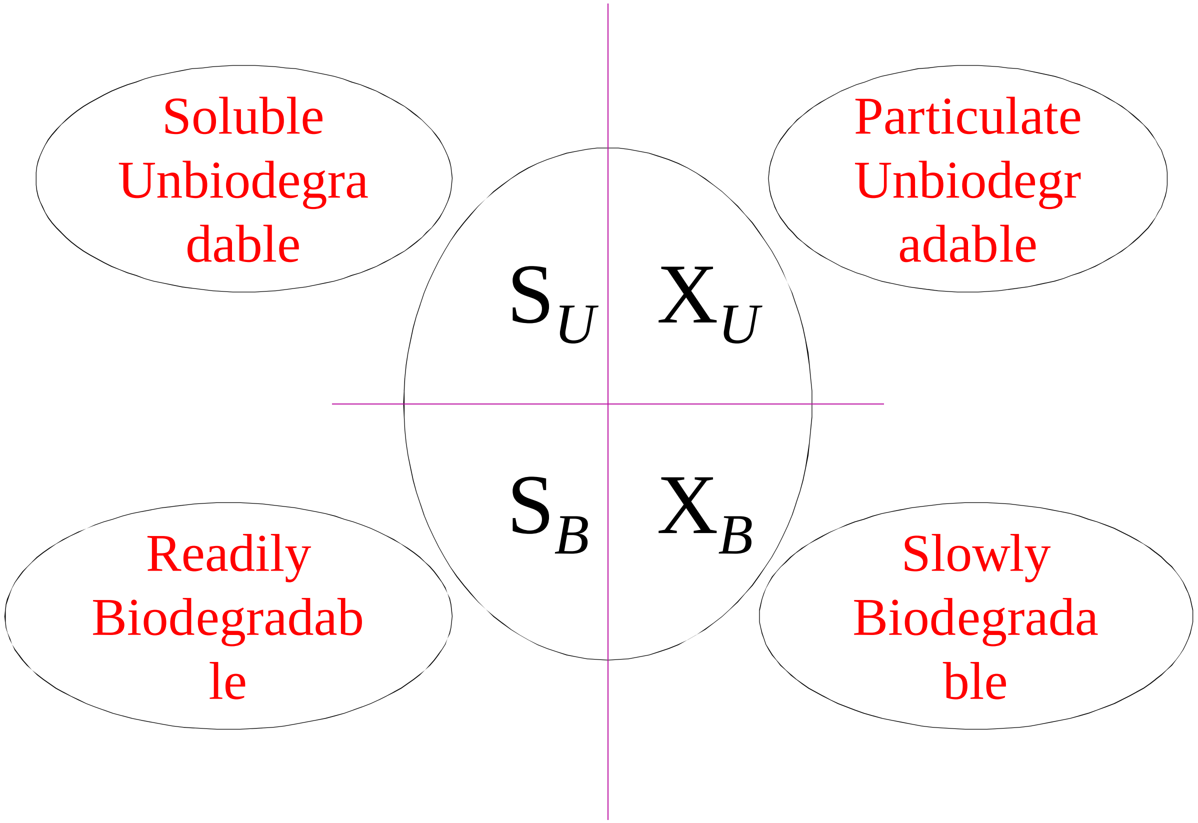
Respirogram



Components contributing to measured OUR

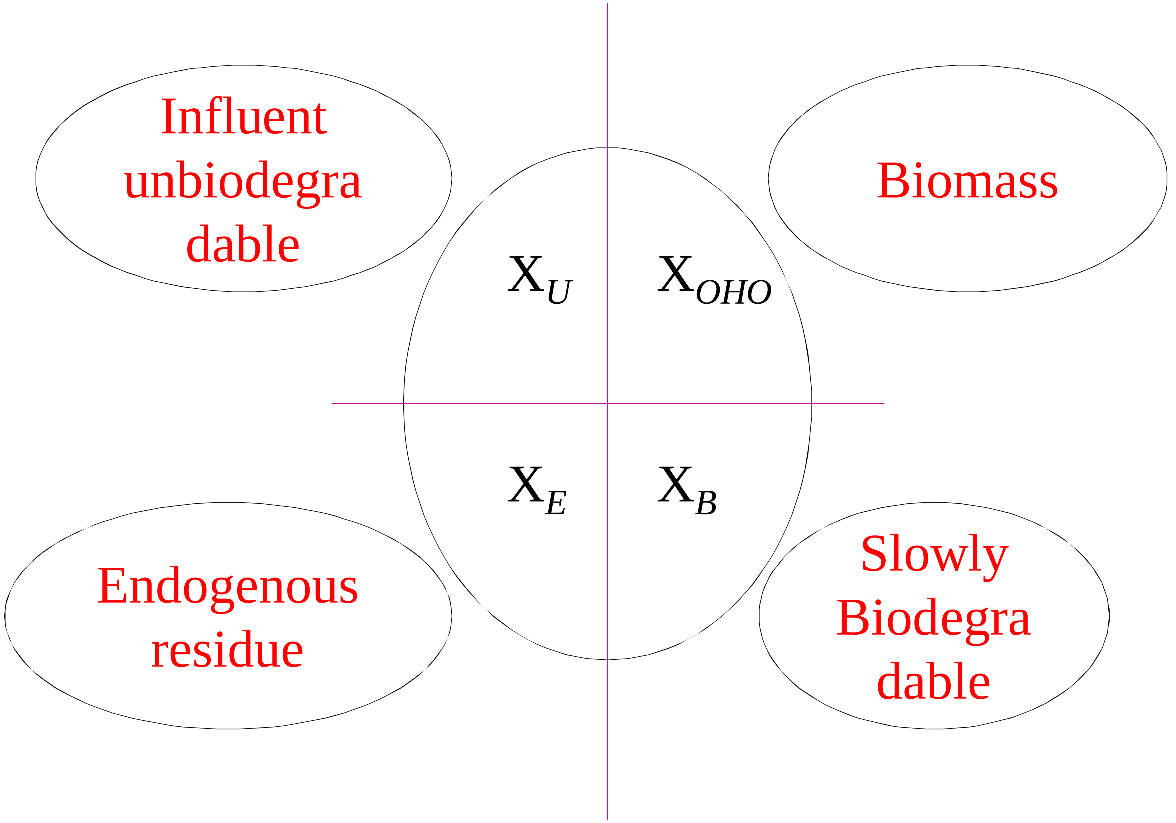


Activated Sludge Model No. 1 - Influent



Four wastewater fractions, at least!

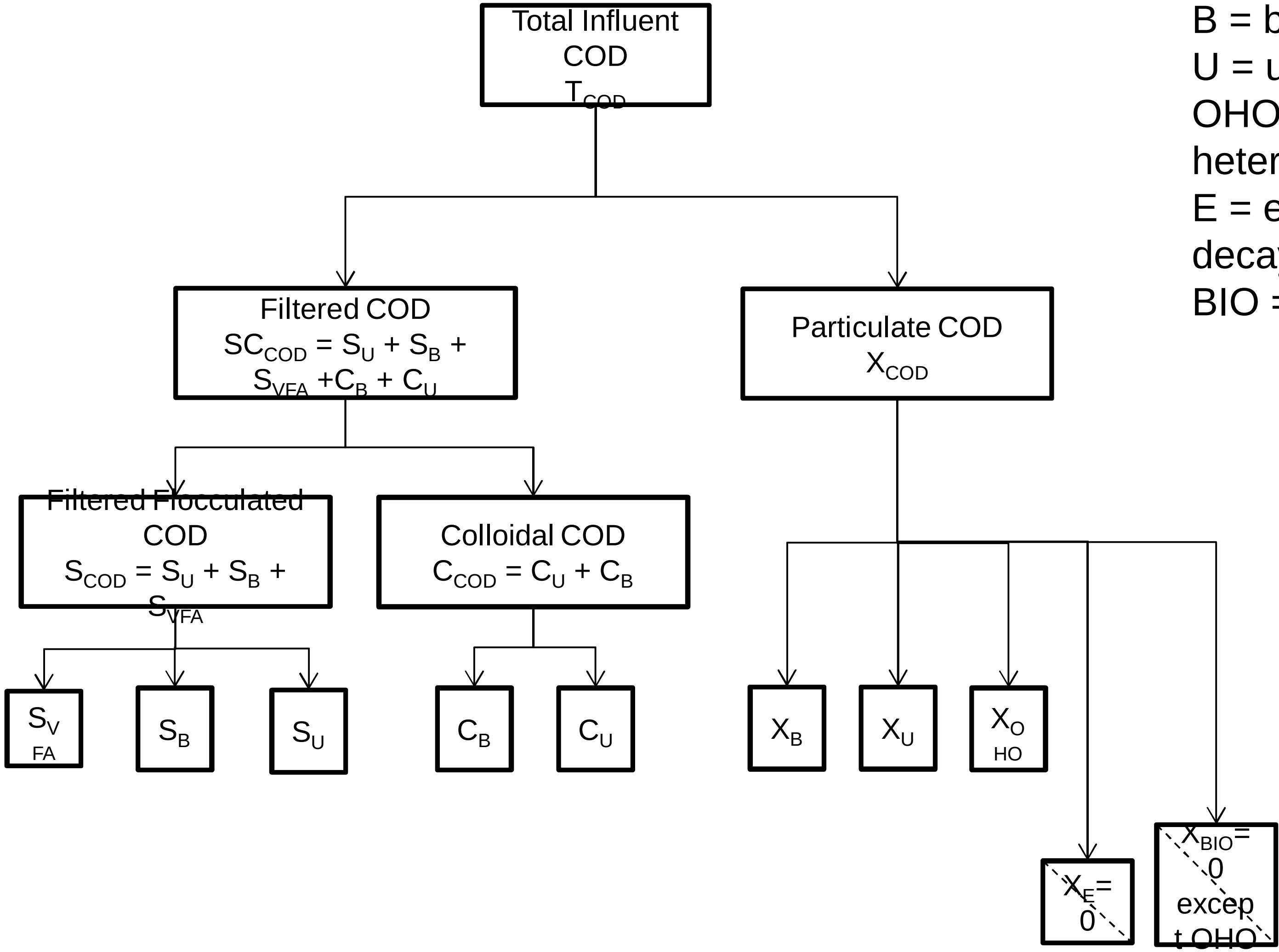
Activated Sludge Model No. 1 - MLSS



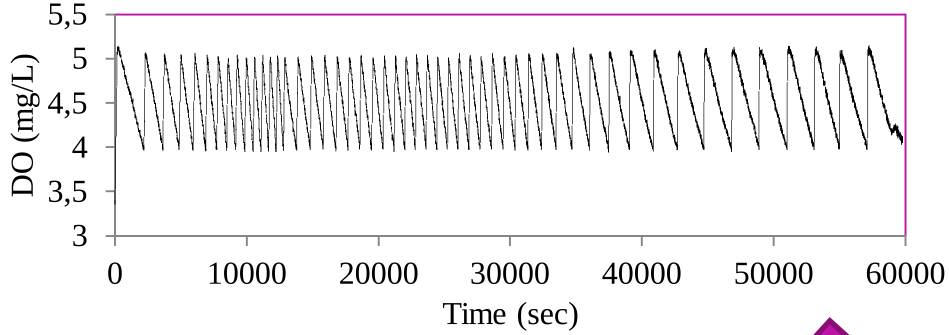
Four biomass fractions, at least!

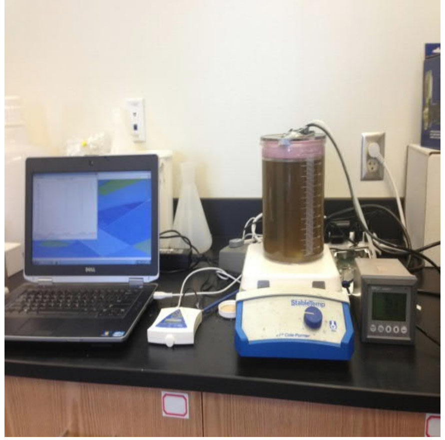
SUMO 1 Influent Fractions

S = soluble
C = colloidal
X = particulate
VFA = volatile fatty acid
B = biodegradable
U = unbiodegradable
OHO = ordinary heterotrophs
E = endogenous decay products
BIO = biomass



Influent OHO measurement





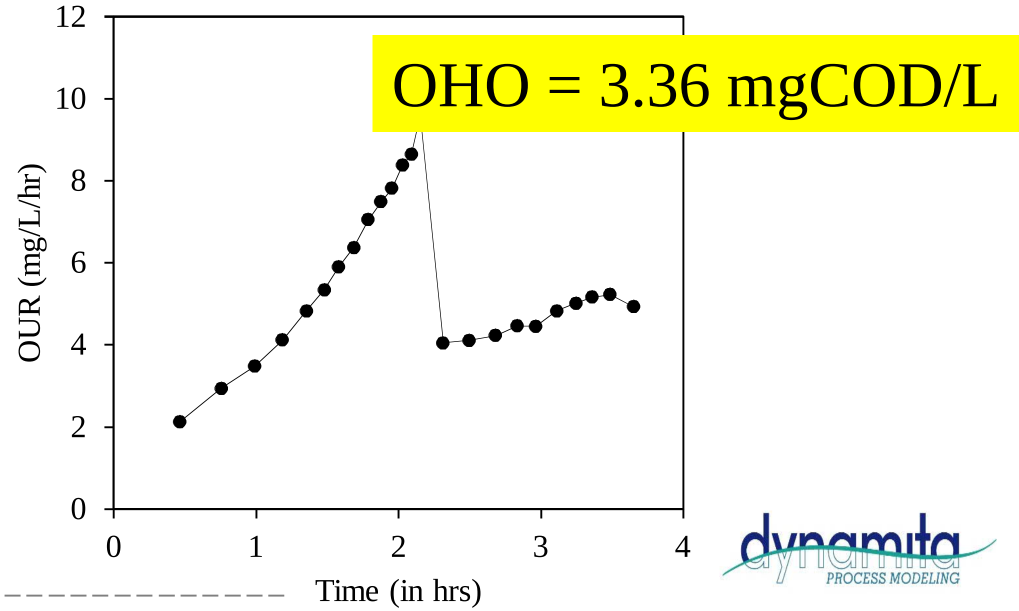


Table 6-2. Example Calculation of Particulate Unbiodegradable Portion of Influent VSS

Parameter	Concentration (mg/L)	Fraction	Fraction Units
Total COD	400		
Soluble unbiodegradable COD	20	0.05	(mg COD/mg total COD)
Soluble readily biodegradable COD	80	0.20	(mg COD/mg total COD)
Slowly biodegradable COD	248	0.62	(mg COD/mg total COD)
Particulate	186	0.75	(mg COD/mg SBCOD)
Colloidal	62	0.25	(mg COD/mg SBCOD)
Particulate unbiodegradable COD	52	0.13	(mg COD/mg total COD)
VSS*	149		
Particulate unbiodegradable portion of VSS**		0.22	

* VSS = (particulate slowly biodegradable COD + particulate unbiodegradable COD)/1.6

**Particulate unbiodegradable portion of VSS = Particulate unbiodegradable COD/1.6 /VSS

Note: These calculations assume a COD/VSS ratio of 1.6

Sumo influent tool

Key measurements	Value	Unit
Flow	24000.0	MGD or m^3/d
TSS	215.0	mg/L
VSS	180.0	mg/L
TDS	800.0	mg/L
TKN	34.4	mgN/L
TP	4.3	mgP/L
Total Sulfur	20.0	mgS/L
Alkalinity	350.0	mgCaCO3/L
pH	7.2	-

Key indicators for sanity check	Value	Unit	Usual value in US
VSS/TSS ratio	0.84	-	0.85
Particulate COD/VSS	1.50	mg COD/mg VSS	1.60
Dissolved salts	585.0	mg/L	
Alkalinity in molar units	7.0	meq/L	3 - 8

COD - BOD	Value	Unit
Influent COD	420.0	mgCOD/L
Influent filtered COD	150.0	mgCOD/L
Influent filtered flocculated COD	80.0	mgCOD/L
Effluent filtered COD (inert)	20.0	mgCOD/L
Influent $cBOD_5$	190.0	mgBOD/L

Particulate COD	270.00	mg COD/L	
Filtered COD fraction	0.36	-	0.40
Filtered flocculated COD fraction	0.19	-	0.20
Unbiodegradable fraction of filtered COD	0.05	-	0.05
COD/BOD ratio	2.21	-	2.20

Help | **Data** | Check fractions | Sumo forms | Balances | Diurnal flow | Calculations

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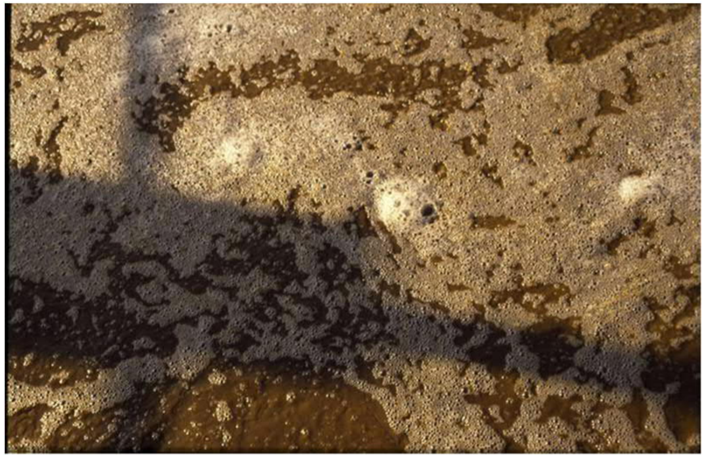
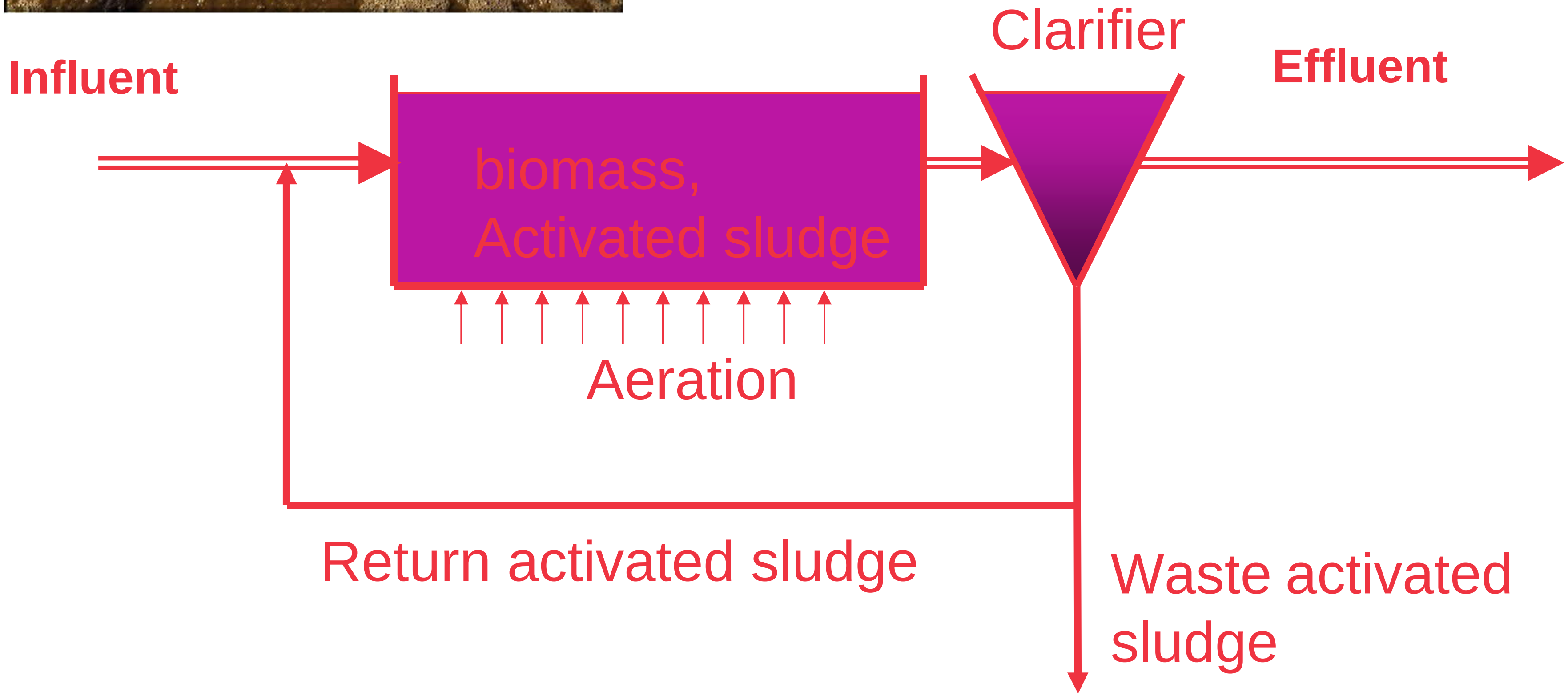
Biological processes
Nutrient removal

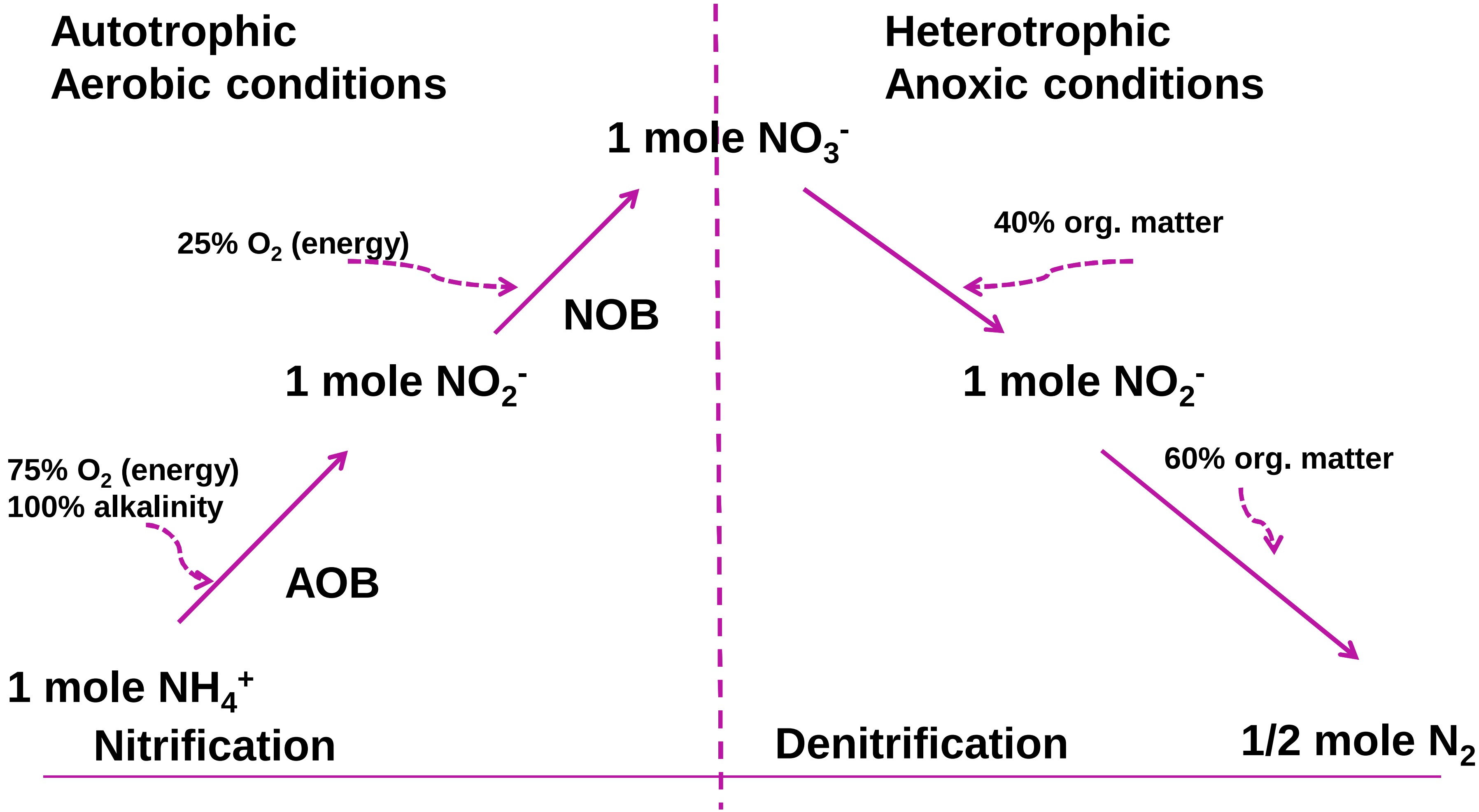
Anna Mikola

Activated sludge process





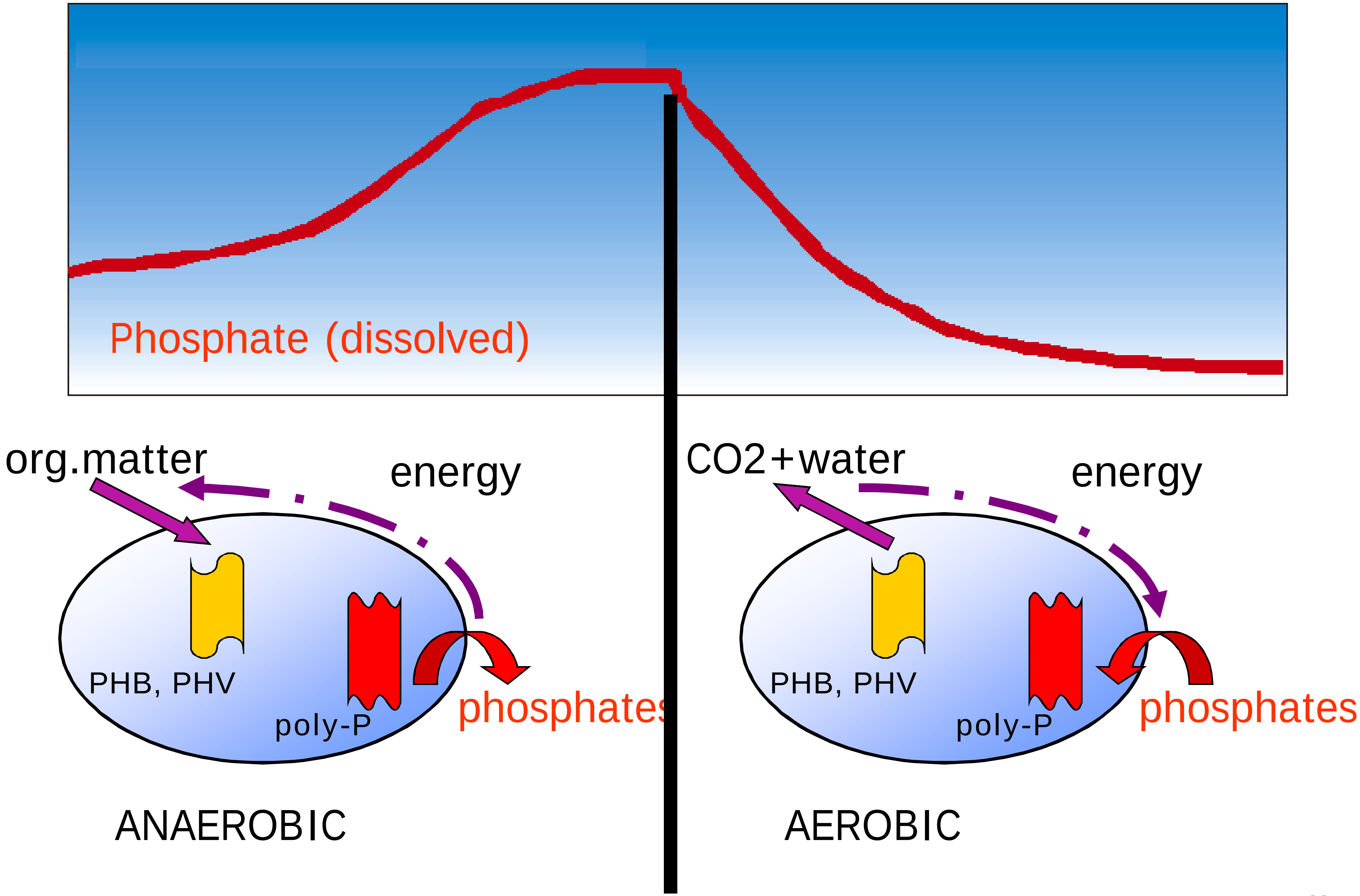
Conventional N removal



Nitrification and denitrification

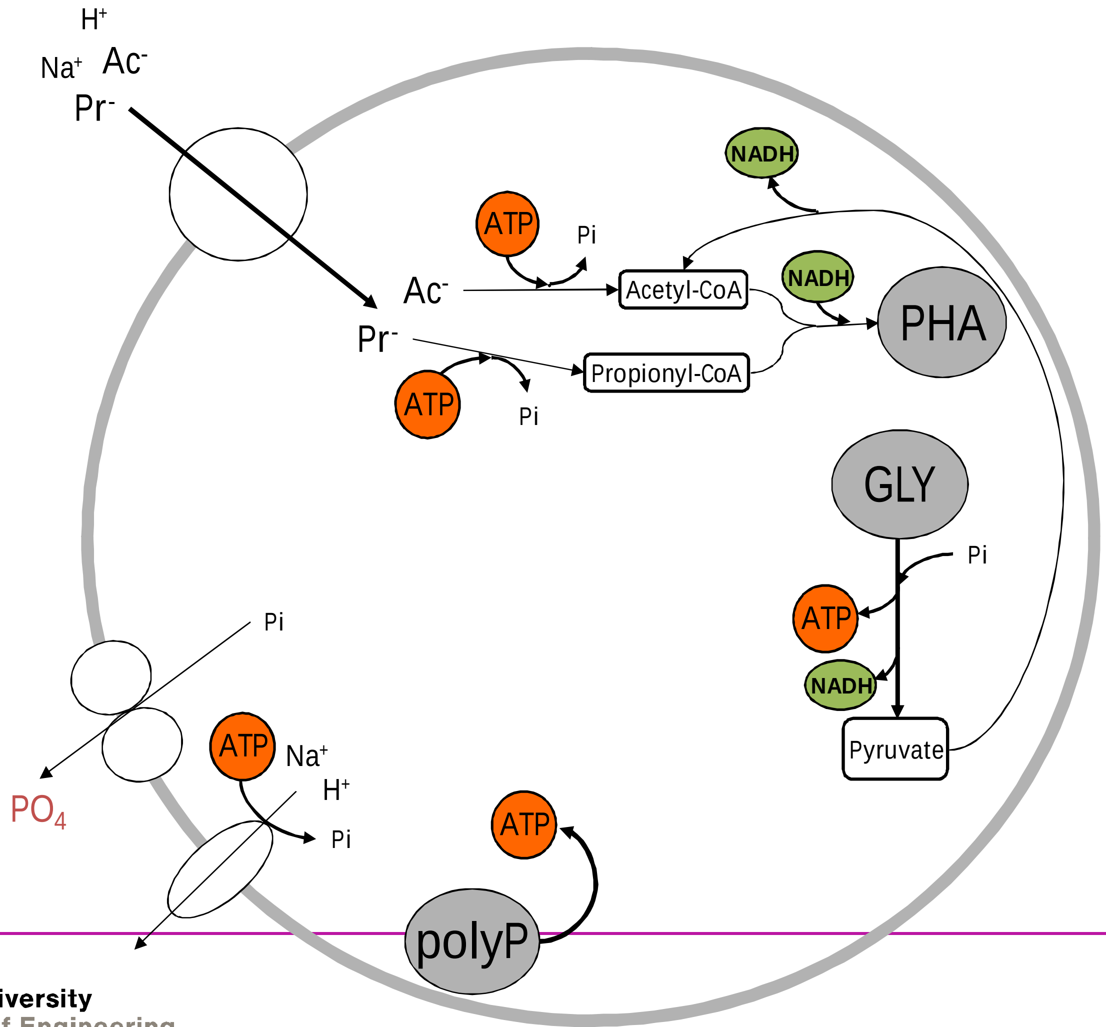
	Nitrification	Denitrification
SRT	long SRT	short SRT increases the rate
Oxygen	high, 2 mg/l	no oxygen or very low
Organic matter	no need (autotrophic)	needs a carbon source
BOD load	low load	high load
Alkalinity	consumes	produces

BioP

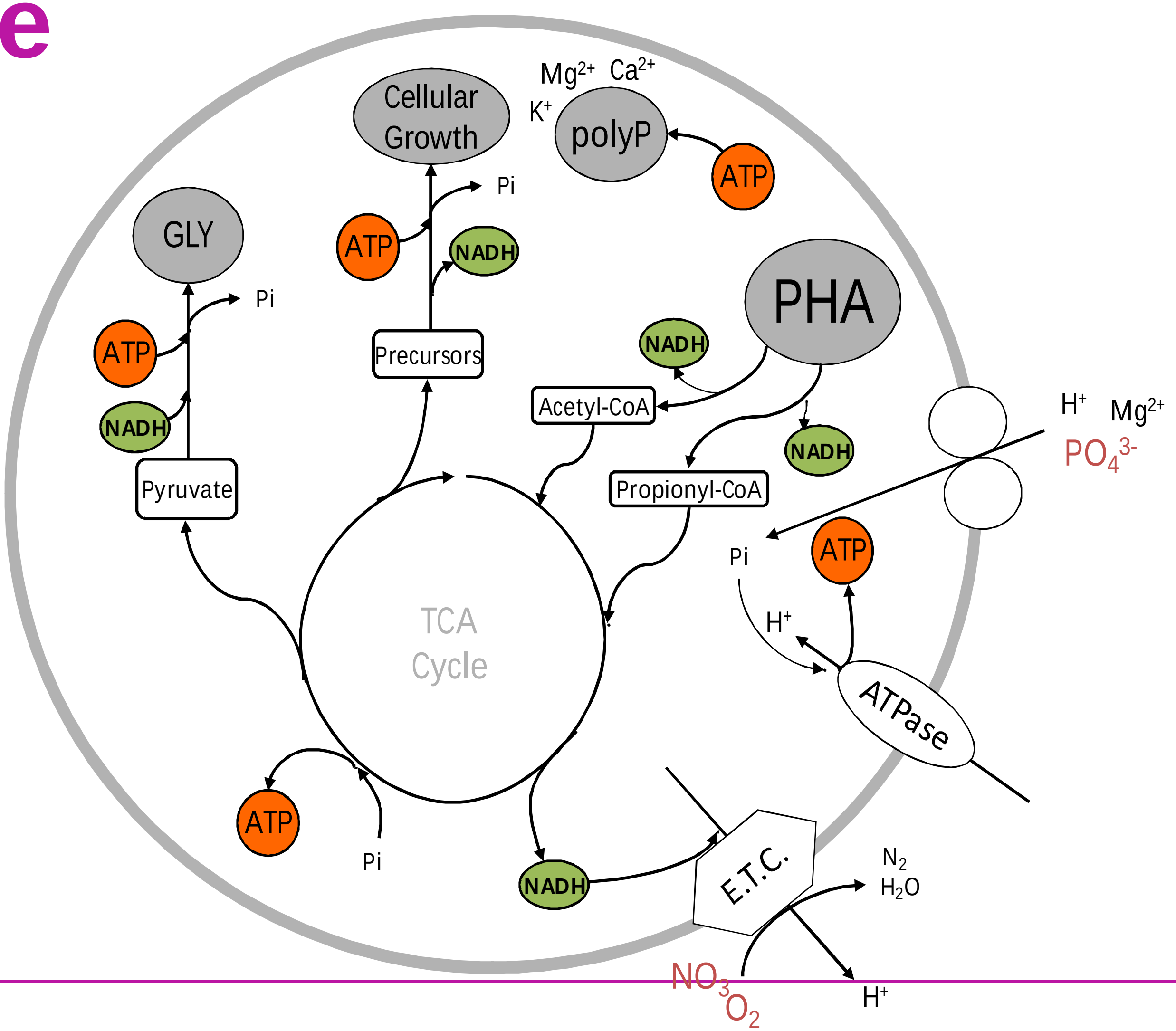


Phosphate (dissolved)
org.matter
energy
PHB, PHV
poly-P
phosphates
ANAEROBIC
CO2+water
energy
PHB, PHV
poly-P
phosphates
AEROBIC

Metabolism of bioP: Anaerobic VFA sequestration



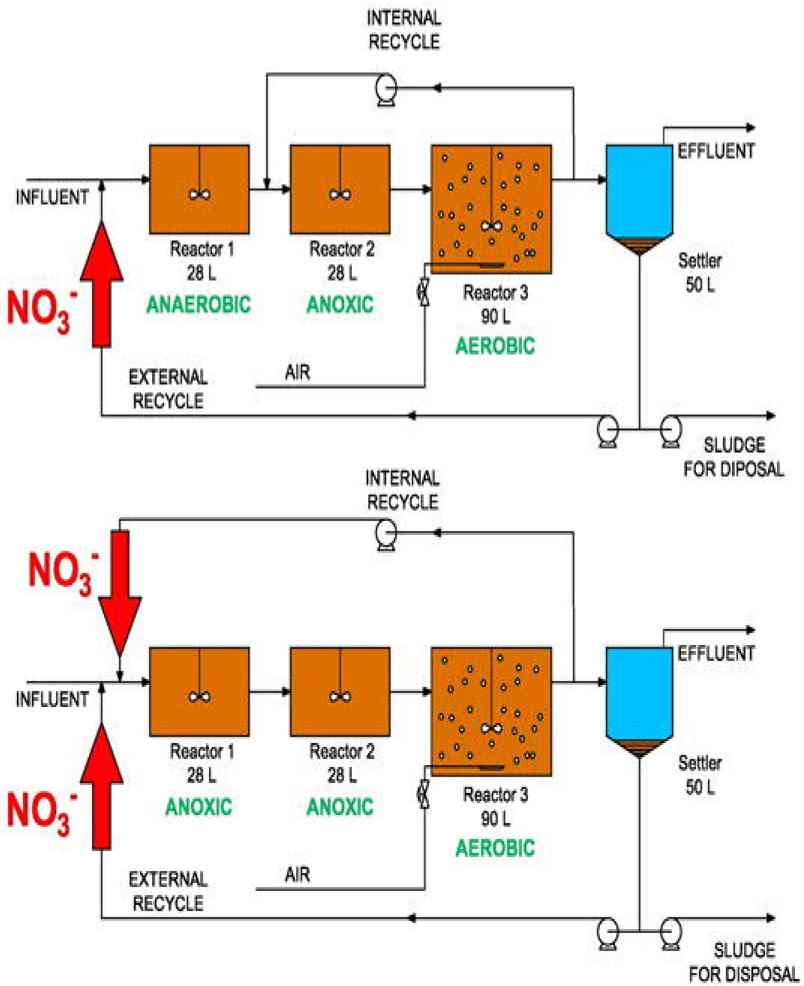
Metabolism of bioP: Aerobic P uptake



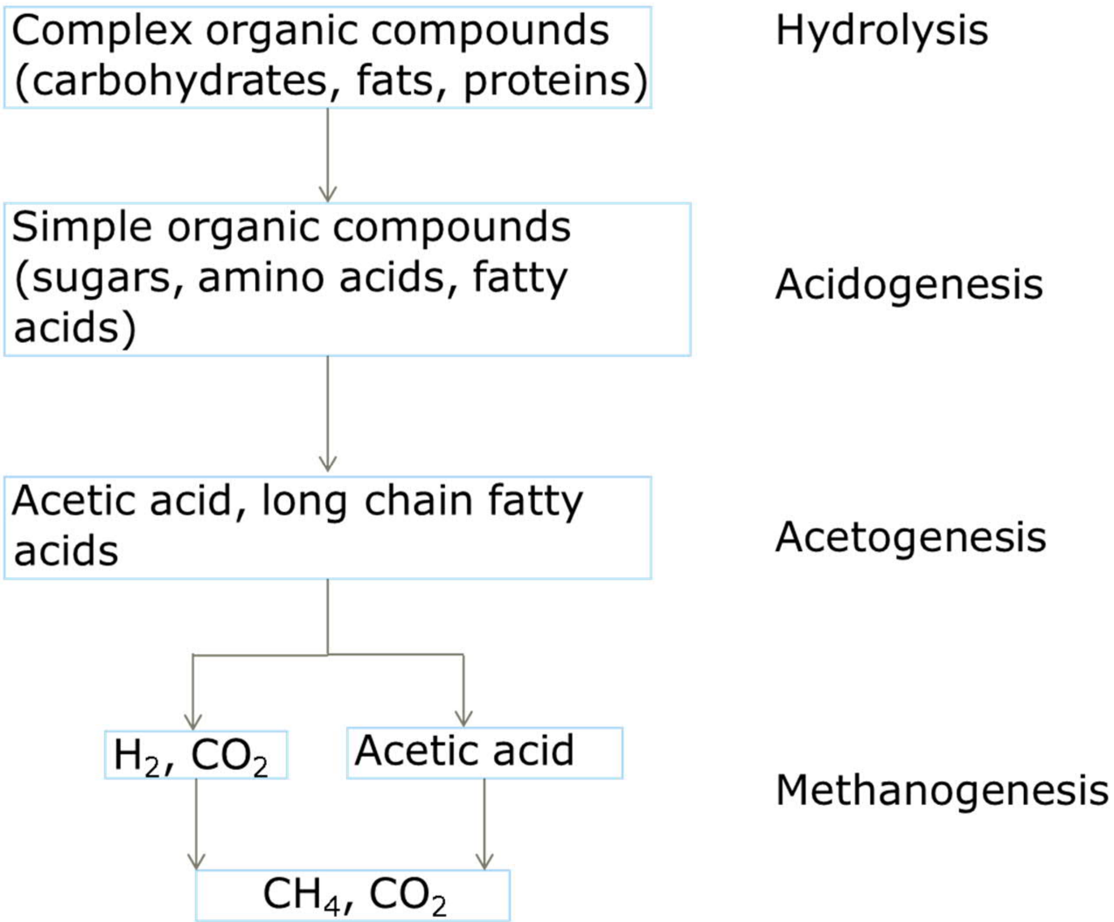
BNR principle

Send NO_X to anoxic zones

Don't send NO_X (or O_2) to anaerobic zones



Anaerobic digestion



Modelling physical processes – particle separation

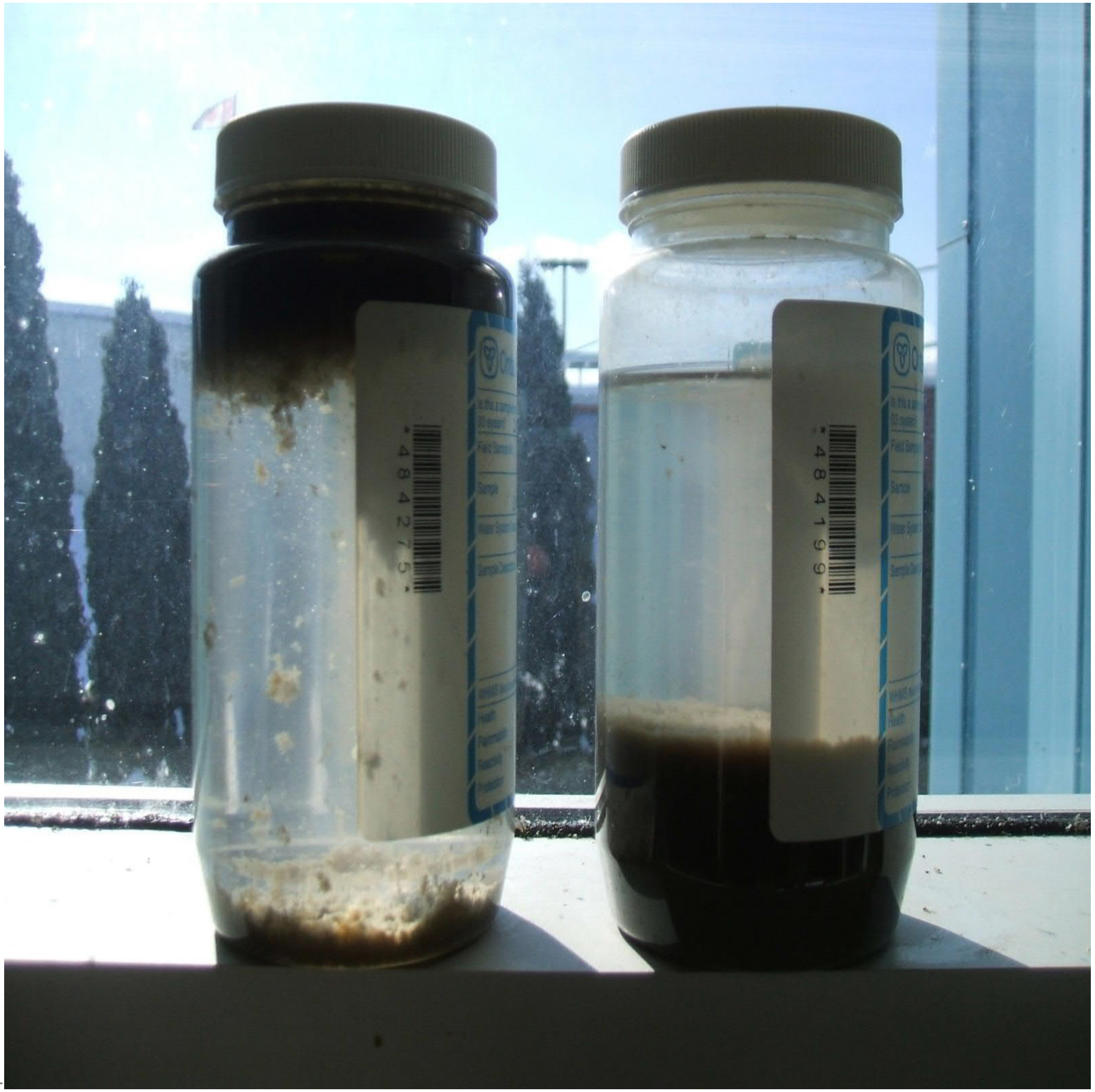
Clarifiers/solid separation

Solid separation options

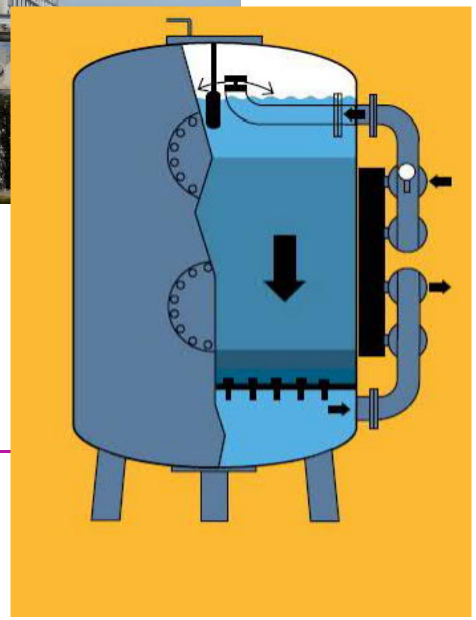
Measures of sludge settleability

Modelling secondary settlers

Settling simplified...



Simple Solids/Liquid Separators



Percent solids removal

- Primary ≈ 65%
- Final ≈ 99.8 %
- Membrane ≈ 100%
- Thickener ≈ 85 – 95 %
- Centrifuge solids capture ≈ 90%
- Sand filter ≈ 70%

Calculated on mass flow basis

Difference provides effluent solids

Secondary or primary settlers

Functions

- Clarification
- Thickening
- Sludge storage

Also reactive

- **often denitrification**
- **Redox varying in the sludge blanket**

Modelling clarifiers and solid separation

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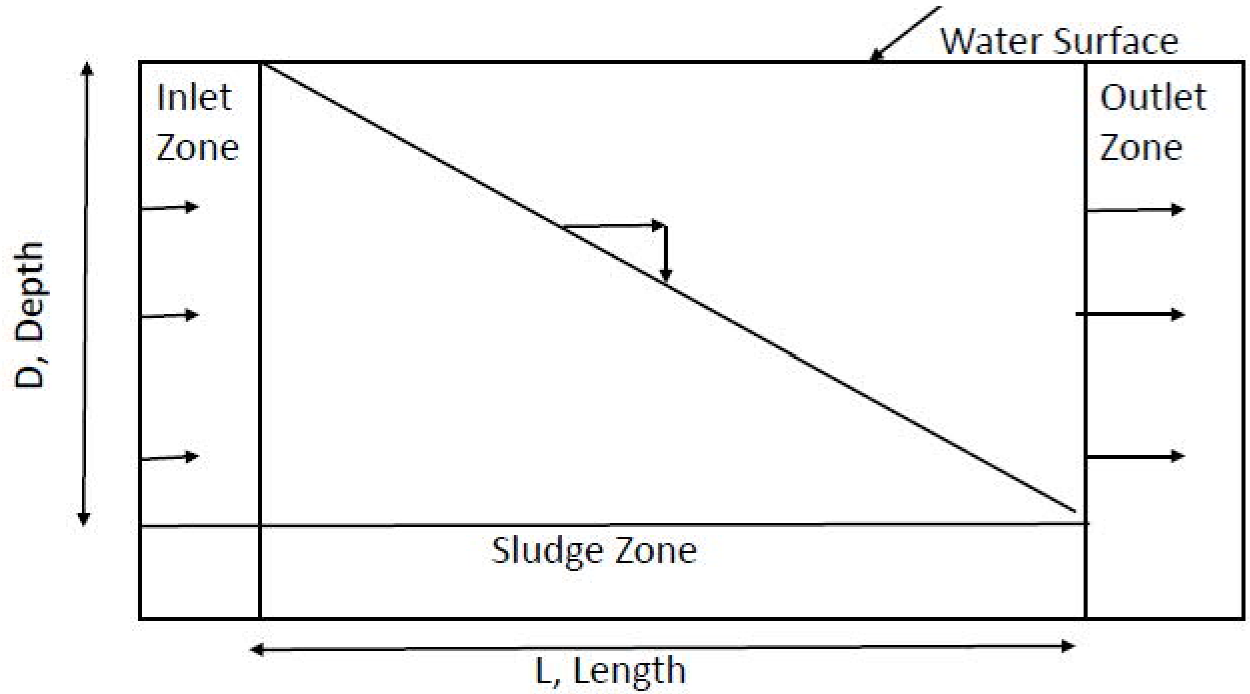
Clarifier theory



Particles that settle faster than the hydraulic retention time of the basin are removed.

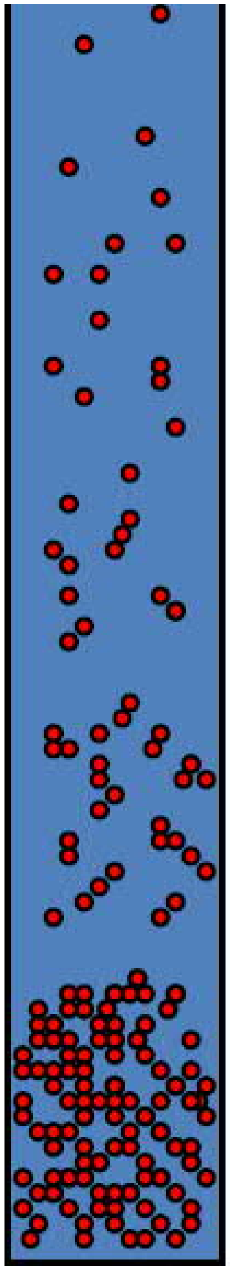
Settling Classes or Types

Discrete
Settling of dilute suspensions, little or no tendency to flocculate

Flocculent
Settling of dilute suspensions with flocculation taking place during the settling

Hindered (Zone settling)
Particles settle as a mass; inter-particle forces hold them in fixed position, settlement in a zone

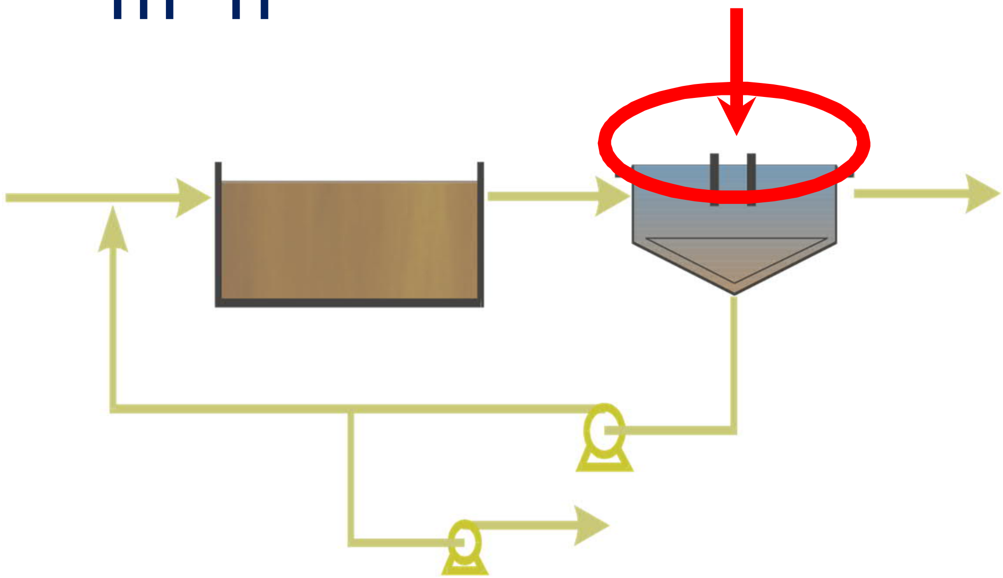
Compressive
Settlement provided by the compacting mass resulting from particles that are in contact



Adapted from Prof. Pagilla Illinois Institute of technology

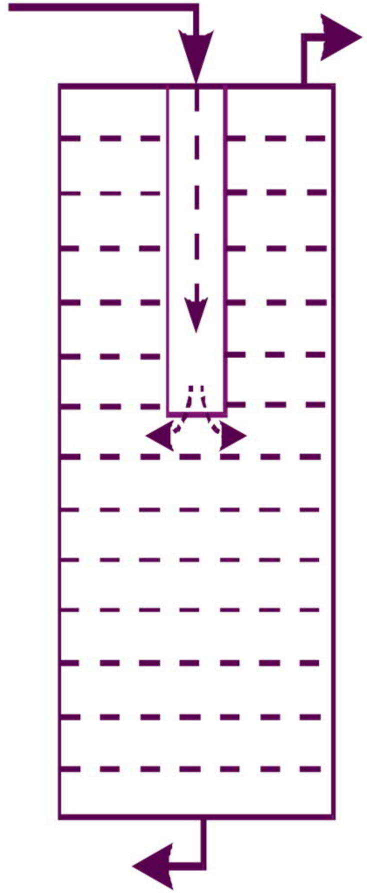
Dimensioning of settlers – based on the loading of solids per surface area

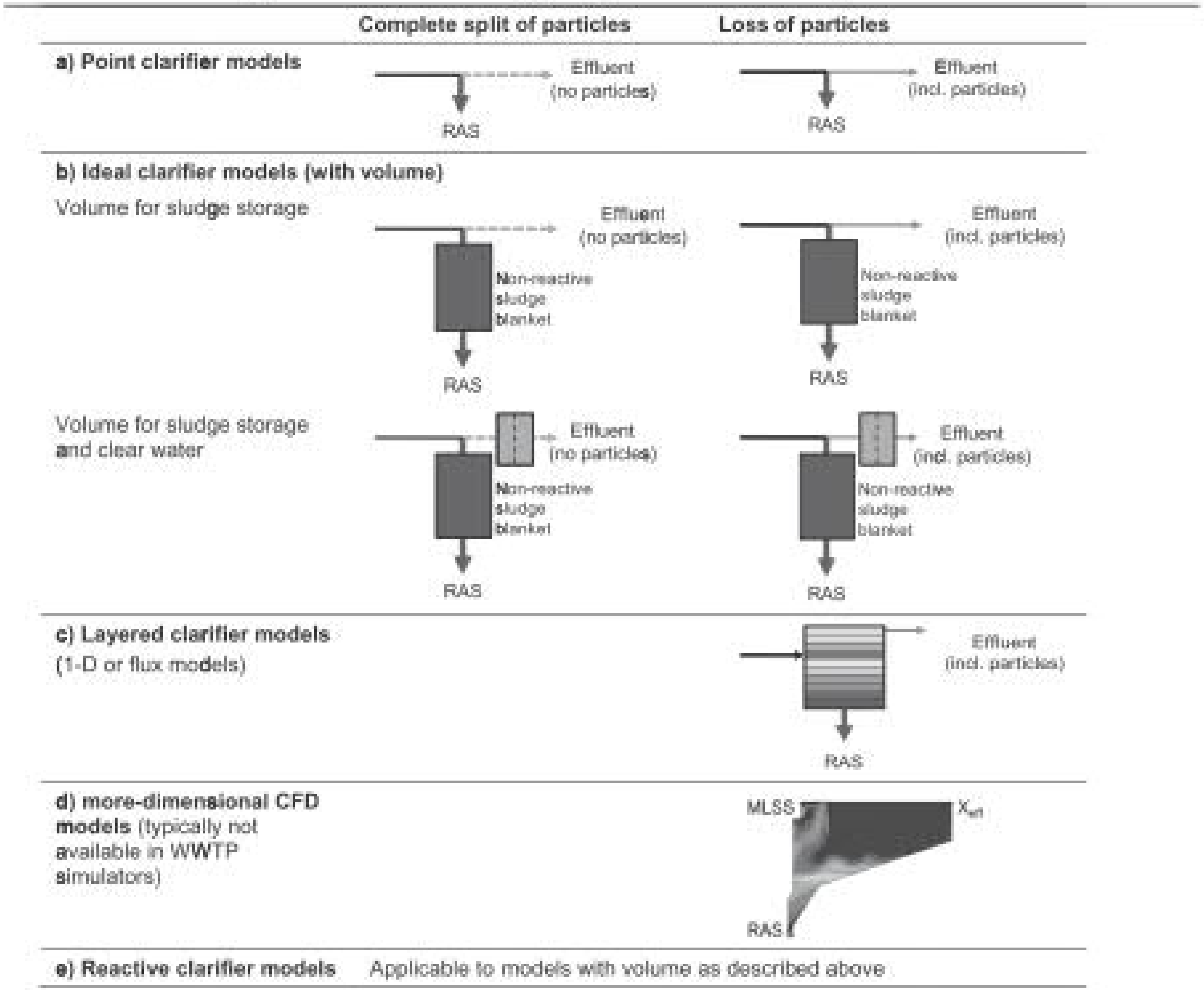
Flux $\frac{\text{kg}}{\text{m}^2 \cdot \text{h}}$



Flux-based settlers

Divide settler into layers



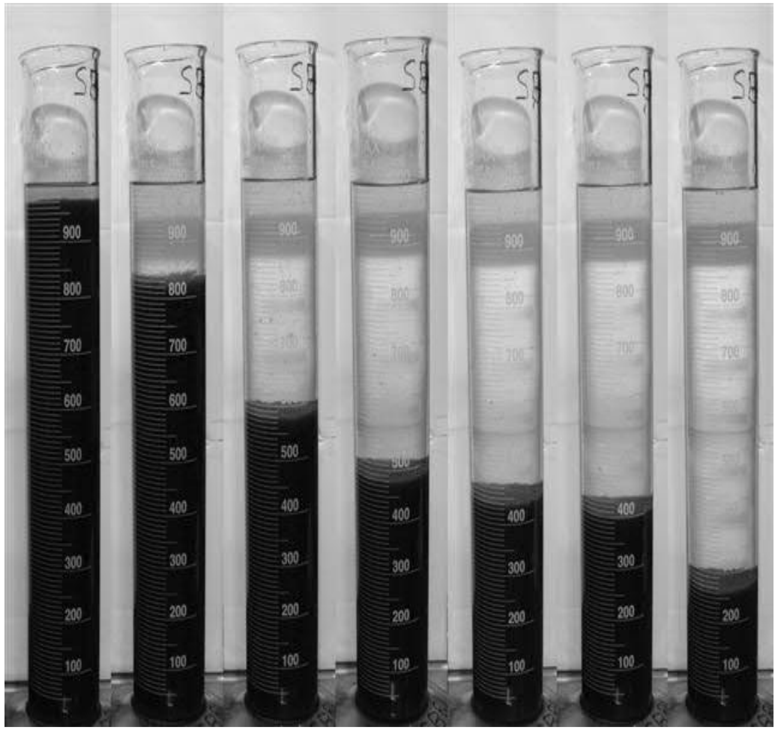

Complete split of particles
Loss of particles
a) Point clarifier models
Effluent
(no particles)
RAS
Effluent
(incl. particles)
RAS
b) Ideal clarifier models (with volume)
Volume for sludge storage
Effluent
(no particles)
Non-reactive
sludge
blanket
RAS
Effluent
(incl. particles)
Non-reactive
sludge
blanket
RAS
Volume for sludge storage
and clear water
Effluent
(no particles)
Non-reactive
sludge
blanket
RAS
Effluent
(incl. particles)
Non-reactive
sludge
blanket
RAS
c) Layered clarifier models
(1-D or flux models)
Effluent
(incl. particles)
RAS
d) more-dimensional CFD
models (typically not
available in WWTP
simulators)
MLSS
RAS
e) Reactive clarifier models
Applicable to models with volume as described above

Measures of sludge settleability

ZSV Zone Settling Velocity

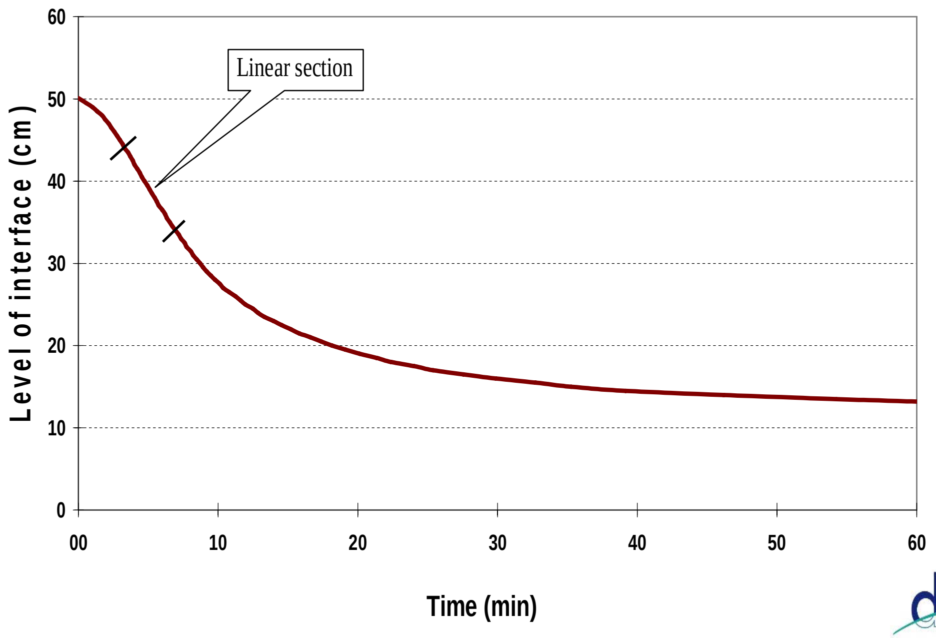
Interface subsidence rate in m/h

Standard: stirred (SZSV)



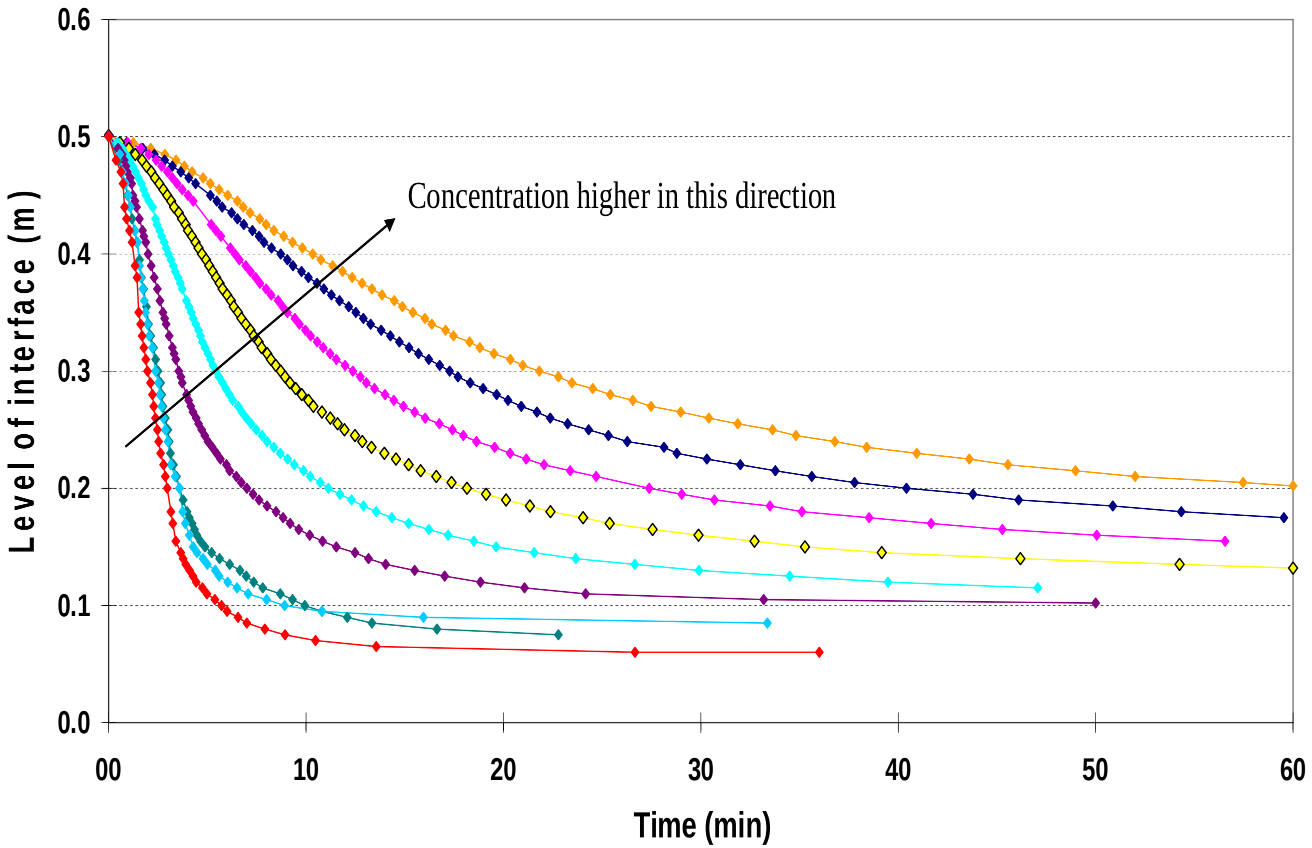
Zone settling velocity test

- Lag phase
- Linear phase
- Compression phase



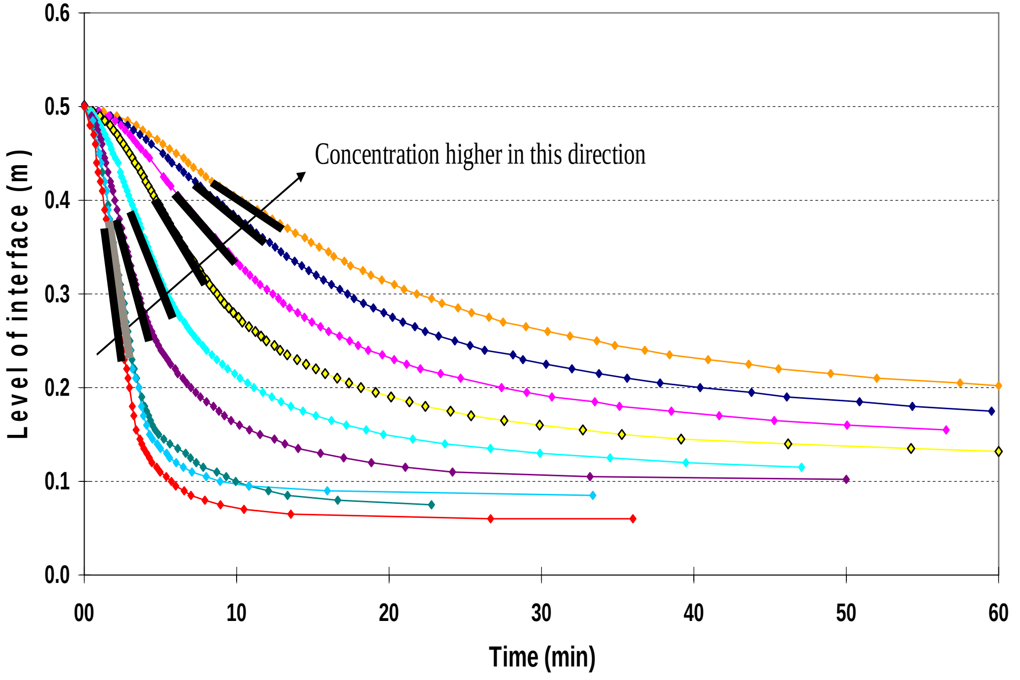
Zone settling velocity test

– Repeat on range of MLSS



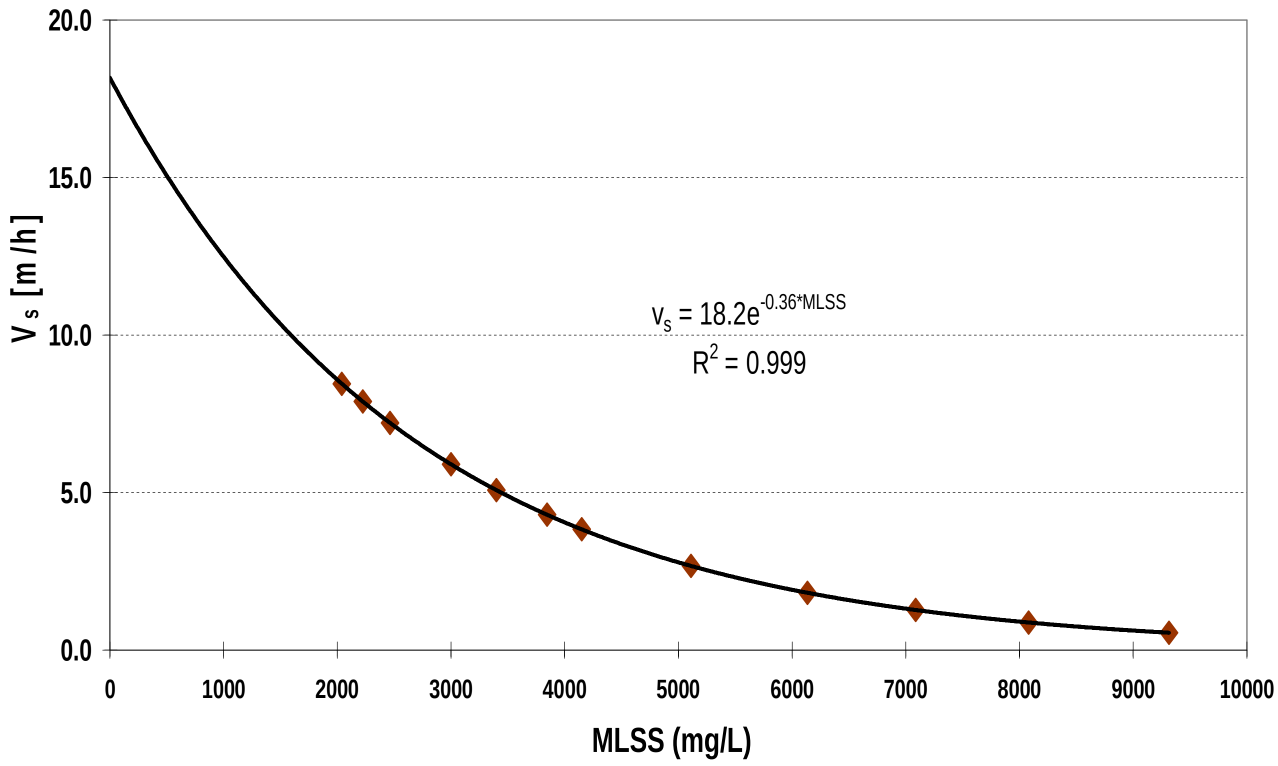
Vesilind settling function

– Read SZSV test slopes



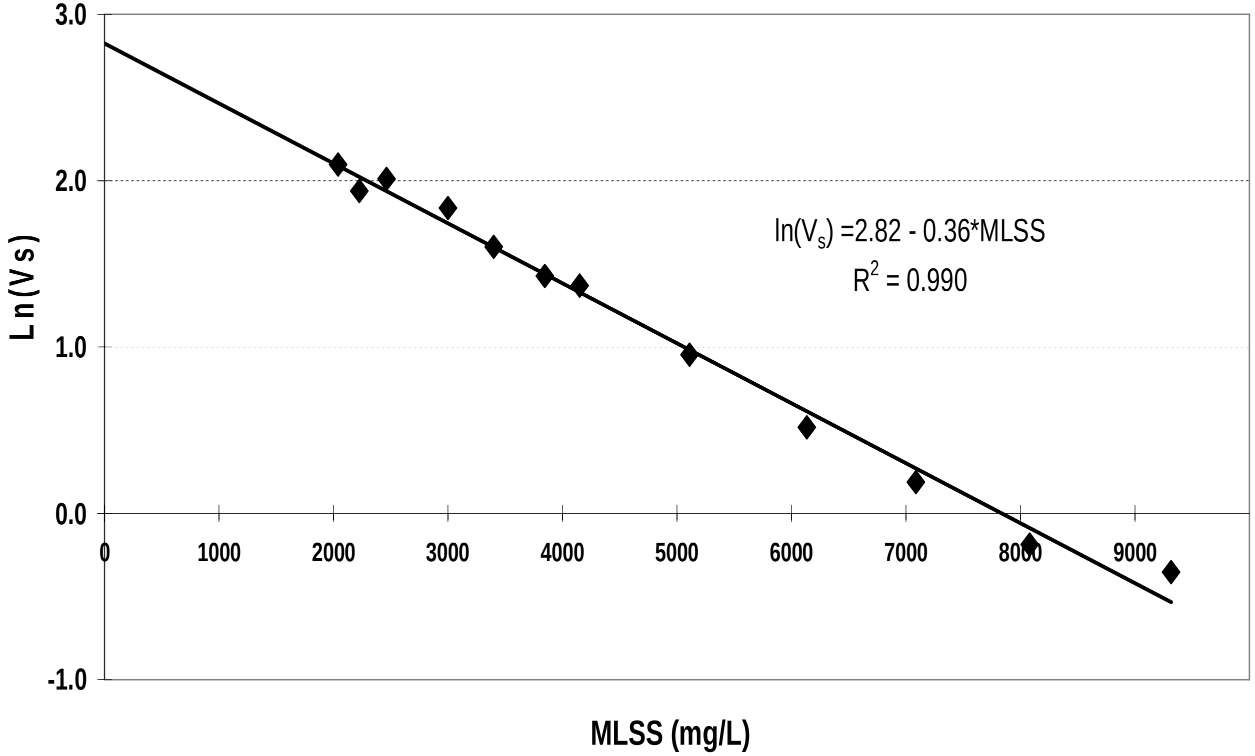
Vesilind settling function

- Evaluation



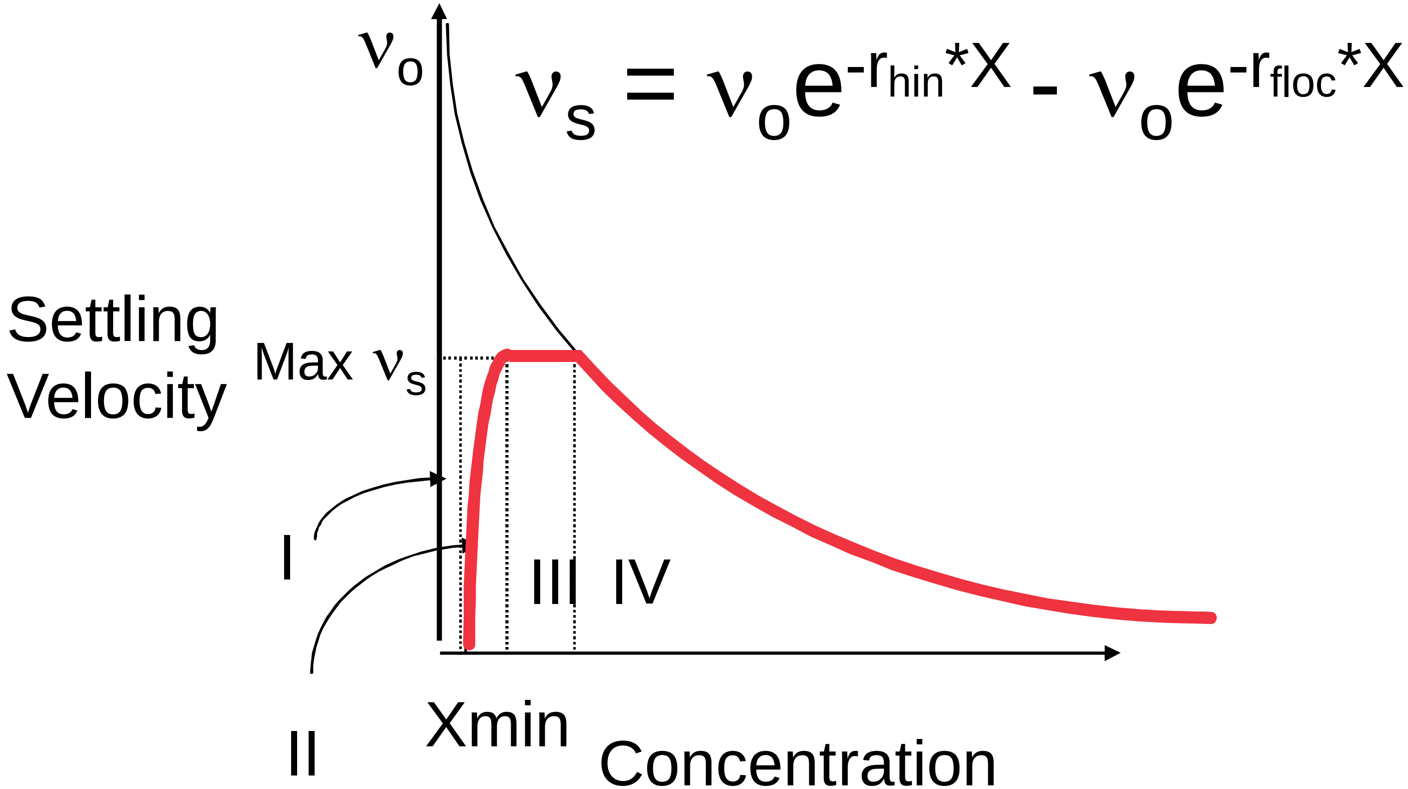
Vesilind settling function

- Evaluation



Double exponential model

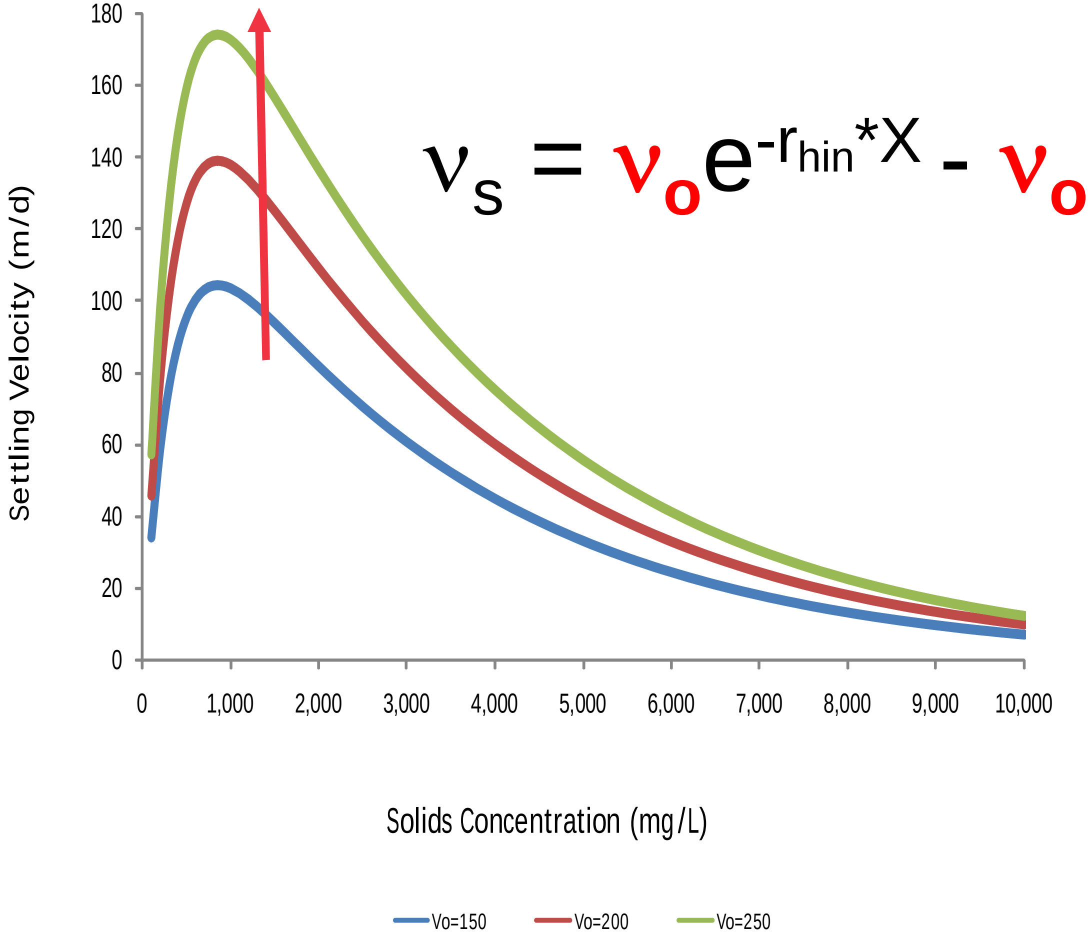
Settling regions



Double exponential model

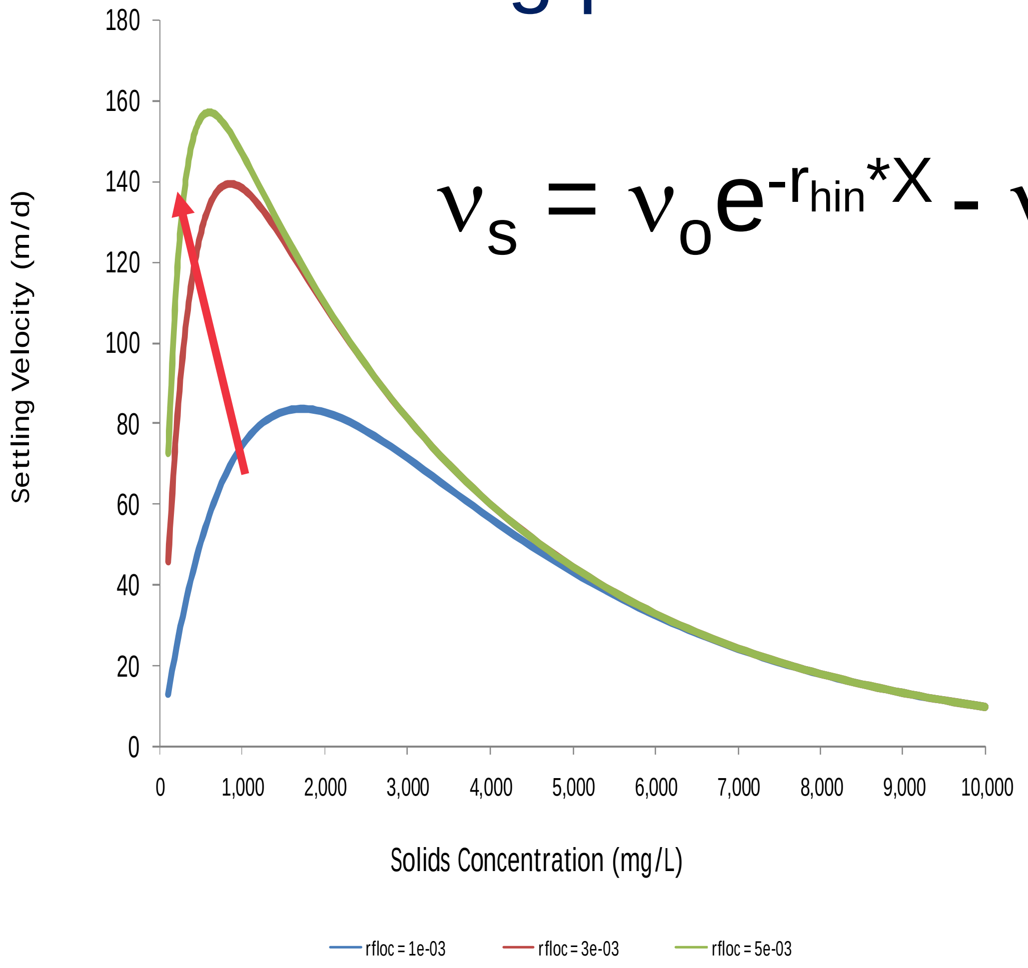
Max. settling velocity

$$\nu_s = \nu_o e^{-r_{hin} * X} - \nu_o e^{-r_{floc} * X}$$



Double exponential model

Flocculent settling parameter

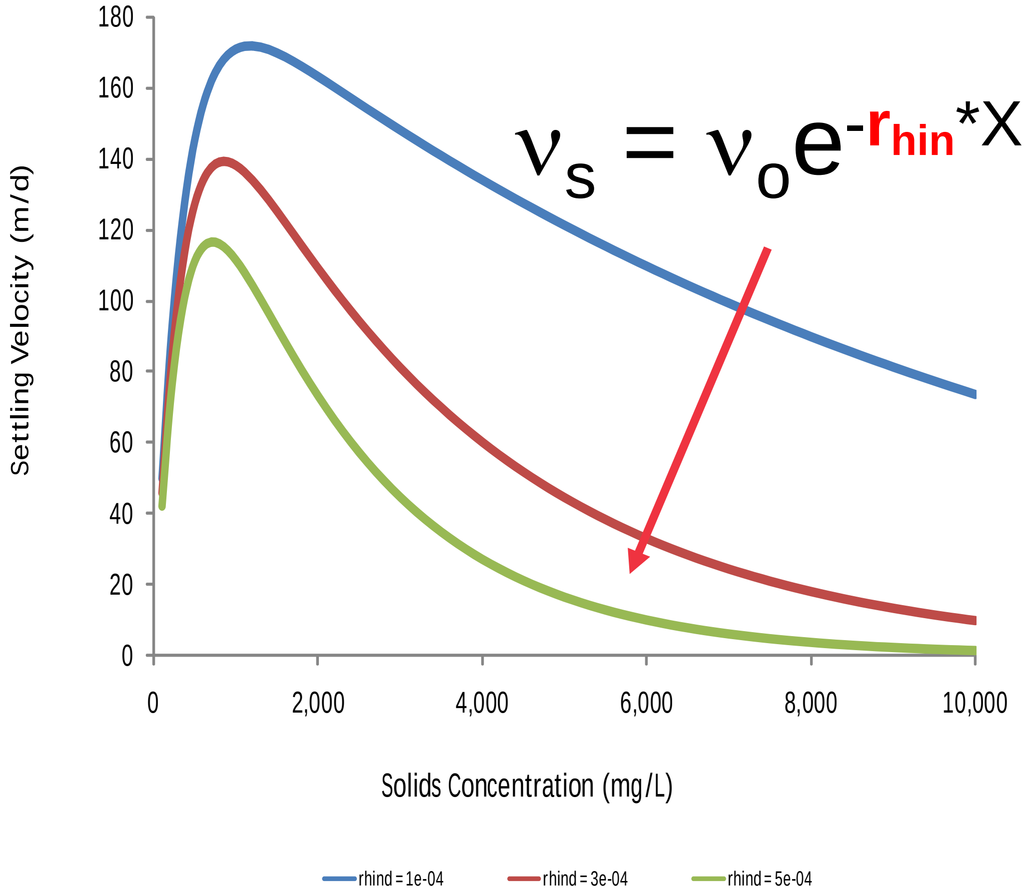


$$\nu_s = \nu_o e^{-r_{hin} * X} - \nu_o e^{-\mathbf{r_{floc}} * X}$$

Double exponential model

Hindered settling parameter

$$\nu_s = \nu_o e^{-r_{hin}*X} - \nu_o e^{-r_{floc}*X}$$



Default dbexp model parameters

Double exponential parameters	**Unit**	**Normal sludge**	**Bulking sludge**	**Old sludge**
Maximum Vesilind settling velocity (Vo)	m/d	410	250	410
Maximum (practical) settling velocity (Vo')	m/d	270	200	270
Hindered zone settling parameter (K_h)	L/g	0.4	0.6	0.2
Flocculent zone settling parameter (K_f)	L/g	2.5	3.0	1.5
Maximum non-settleable TSS	mg/L	20	10	30
Non-settleable fraction	-	0.001	0.001	0.002

Modelling chemical processes - pH and chemical P removal

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pH model: components

Weak acid systems

- Carbonate
- Ammonia
- Phosphate
- Acetate, VFAs

Strong cations

- Calcium
- Magnesium
- Other strong cations (Na^+, K^+)

Strong anions (Cl^-, SO_4^{2-})

pH model allows

Gas phase modeling

- Transfer / stripping of CO_2, NH_3
- Species distribution depends on pH

pH inhibition in biological processes

- Low pH
- High pH

Chemical P removal

- Alum, ferric addition for P precipitation

Spontaneous Precipitation

- Struvite
- Ca carbonate and phosphate

Chemical P removal

Principle of chemical phosphorus removal

Chemicals used for phosphorus precipitation

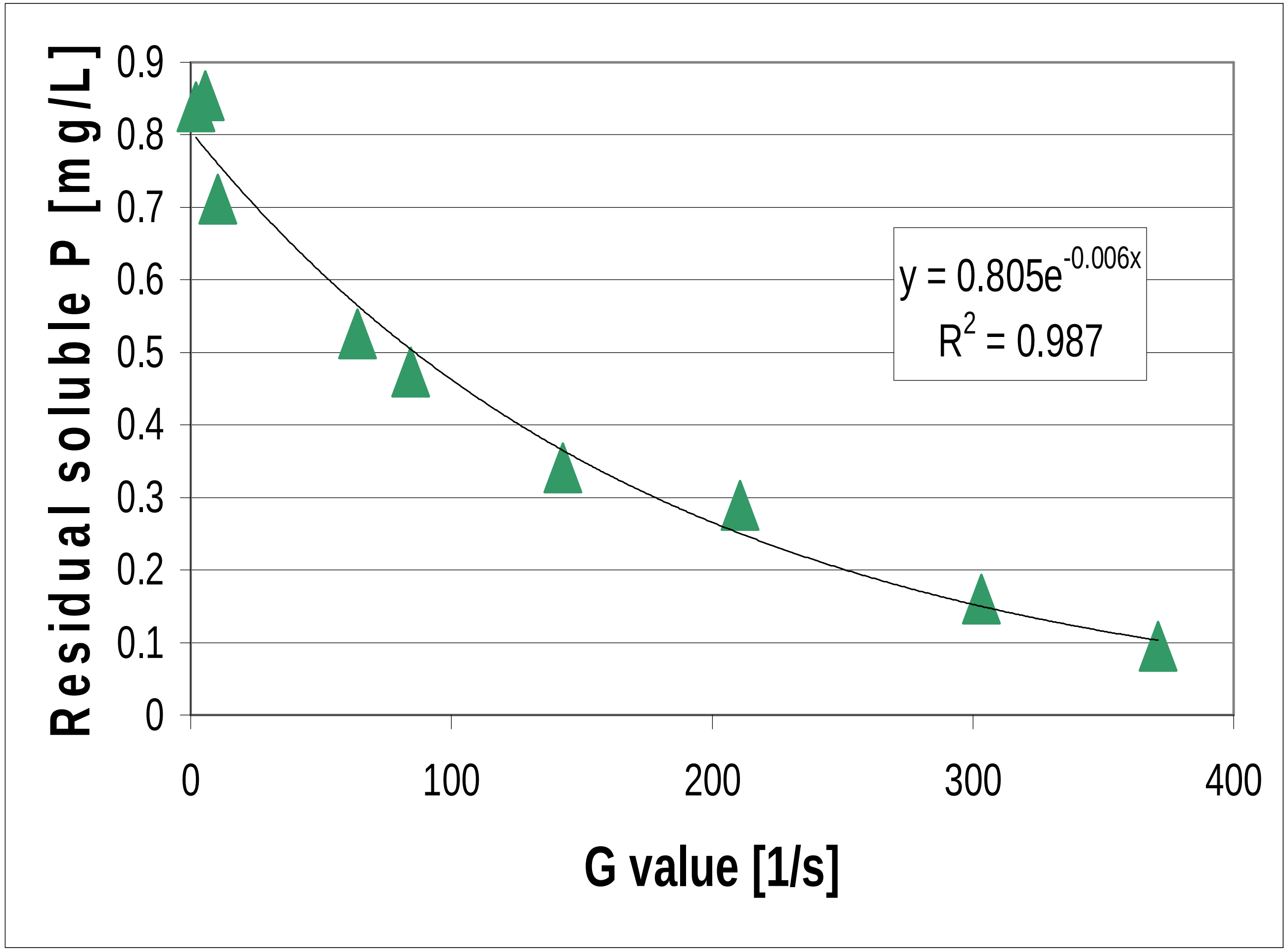
Impacts of chemical addition on plant operation

- **Struvite / calcium phosphate precipitation**
- **Metal salts additions**

Side effects:

- **Inhibition of nitrification**
- **Inhibition of BioP removal**
- **Drop of pH**

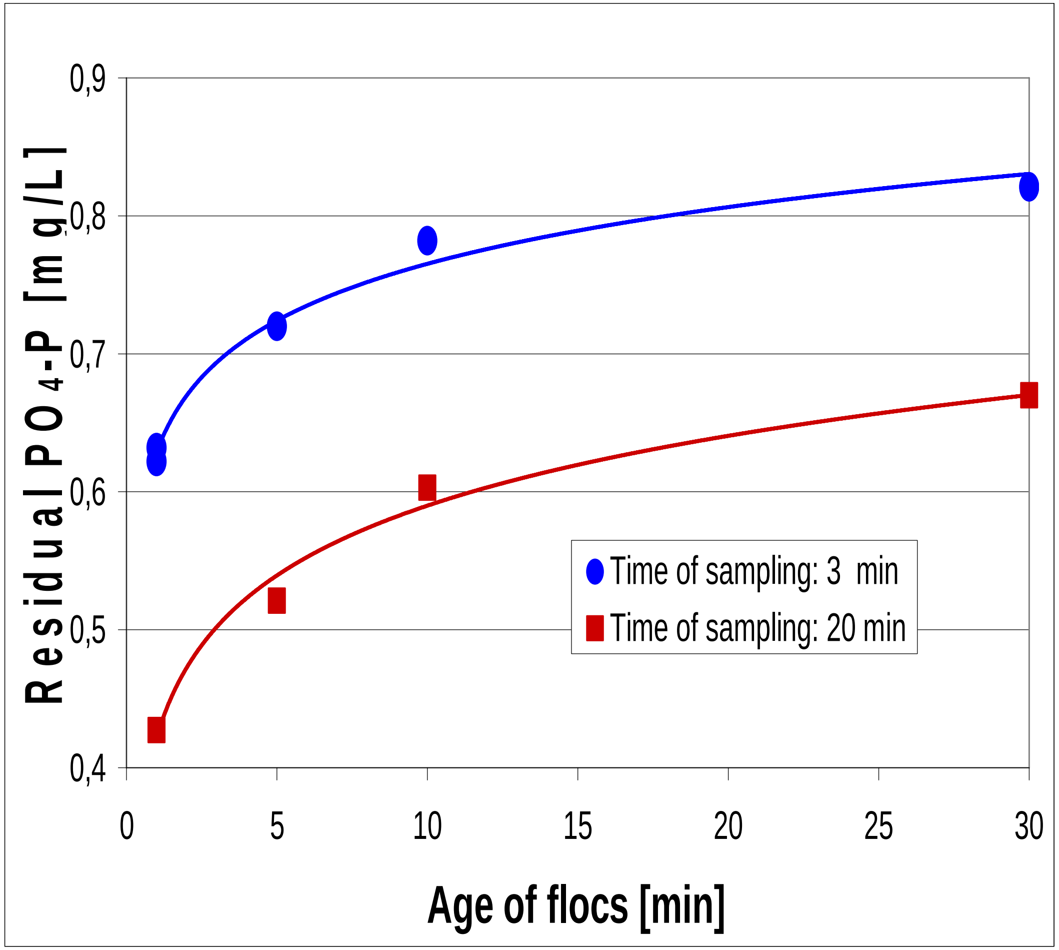
Influence of mixing power (G)



(ferric-chloride; Pini = 4.1 mg/L; Fedose/Pini = 1.8; time of sampling: 11 min after coagulant addition)

Chemical precipitation

- Adsorption on hydroxide flocs



Preformed HFOs; P_{ini} = 1. 0 mg/L; Fe/P = 3.0)

Chemical precipitation

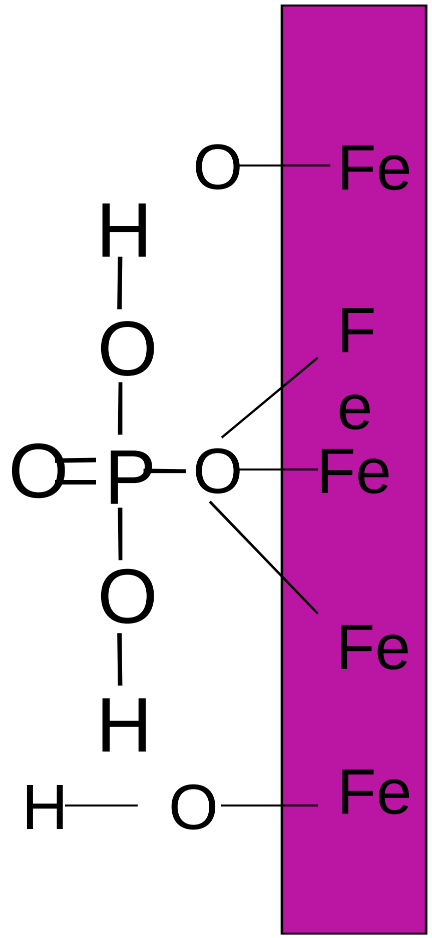
Combined equilibrium and kinetic process

$FePO_4$ crystals form only between pH 2 and 4

"Chemical precipitation" is misleading

- Hydrous ferric oxides precipitate
- Co-precipitation of PO_4
- Diffusion into flocs
- Adsorption (chemi-sorption)
- Coagulation - flocculation

Surface Complexation



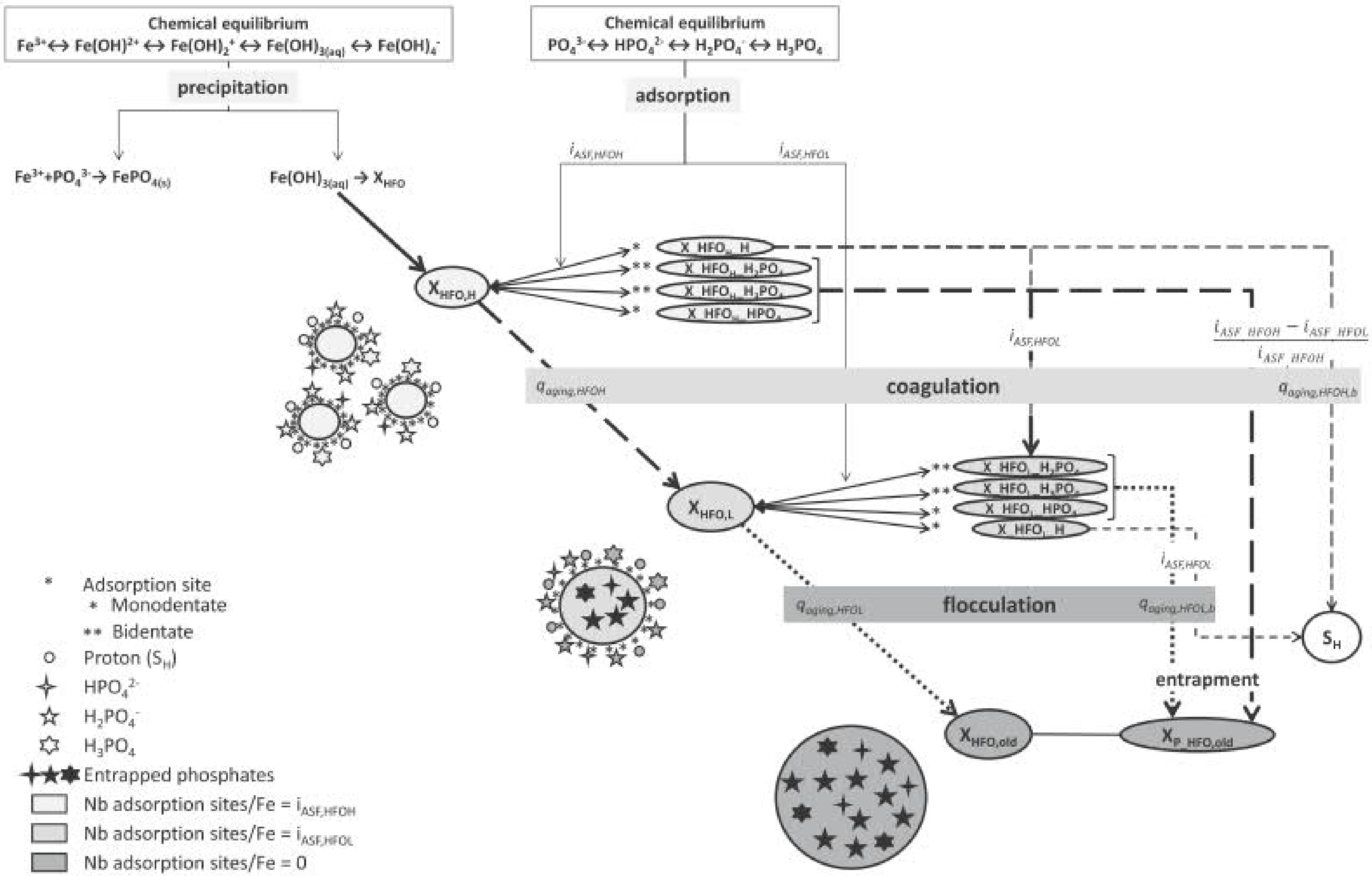
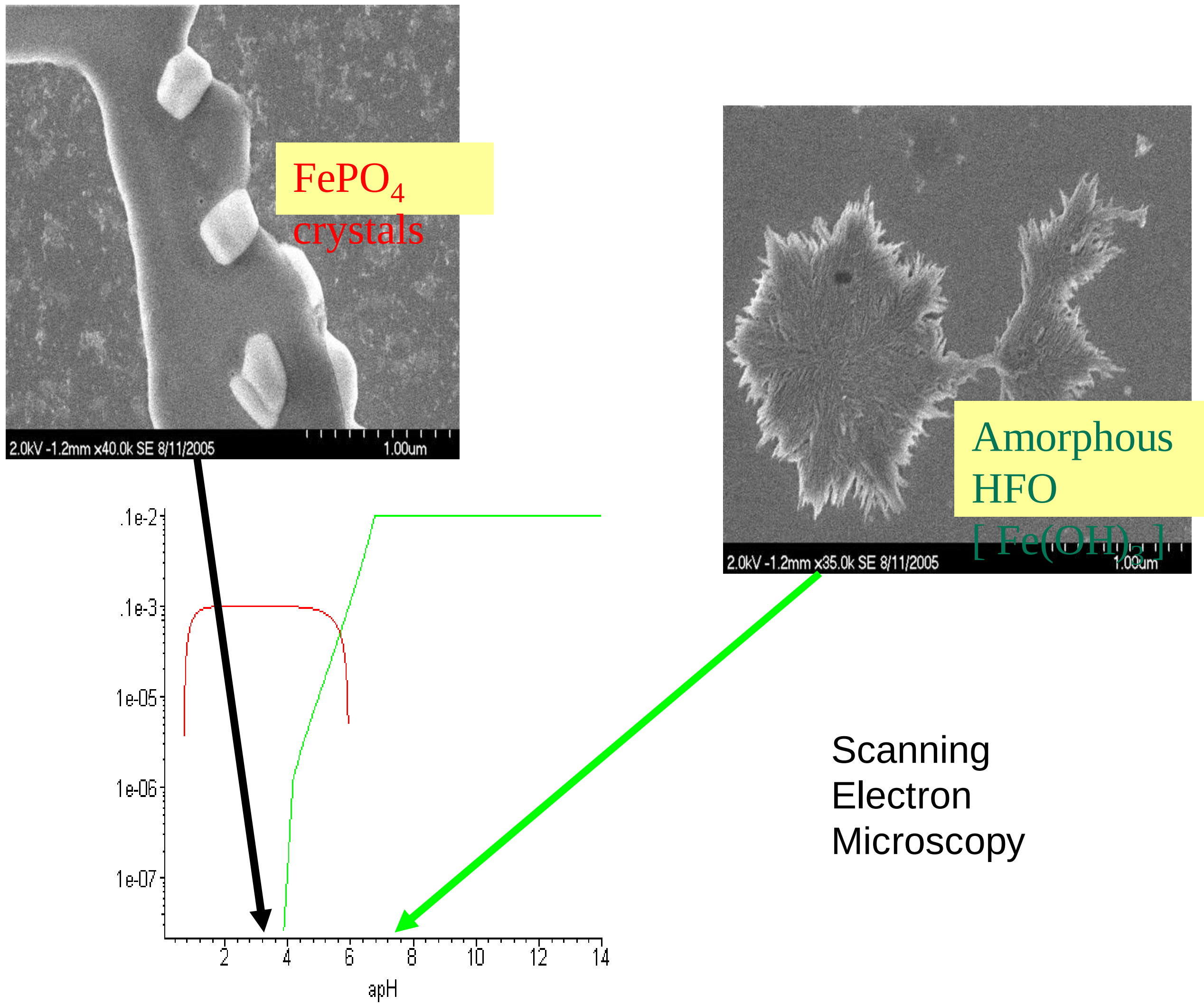


Fig. 1 — Description of adsorption and co-precipitation of phosphate on HFO modelling concepts.

Chemical precipitation

- Under the Microscope



Scanning Electron Microscopy

Table 1 – Reactions considered in the kinetic pH model, chemical ion paring and precipitation model.

1) Chemical Equilibrium Dissociation	
CED_01_H2O	$H_2O \leftrightarrow H^+ + OH^-$
CED_02_H2CO3	$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$
CED_03_HCO3	$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$
CED_04_H3PO4	$H_3PO_4 \leftrightarrow H^+ + H_2PO_4^-$
CED_05_H2PO4	$H_2PO_4^- \leftrightarrow H^+ + HPO_4^{2-}$
CED_06_HPO4	$HPO_4^{2-} \leftrightarrow H^+ + PO_4^{3-}$
2) Chemical Ion Paring	
CIP_01_CaOH	$Ca^{2+} + OH^- \leftrightarrow CaOH^+$
CIP_02_CaCO3	$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$
CIP_03_CaHCO3	$Ca^{2+} + HCO_3^- \leftrightarrow CaHCO_3^+$
CIP_04_CaPO4	$Ca^{2+} + PO_4^{3-} \leftrightarrow CaPO_4^-$
CIP_05_CaHPO4	$Ca^{2+} + HPO_4^{2-} \leftrightarrow CaHPO_4$
CIP_06_CaH2PO4	$Ca^{2+} + H_2PO_4^- \leftrightarrow CaH_2PO_4^+$
CIP_07_FeOH	$Fe^{3+} + OH^- \leftrightarrow FeOH^{2+}$
CIP_08_FeOH2	$FeOH^{2+} + OH^- \leftrightarrow Fe(OH)_2^+$
CIP_09_FeOH3	$Fe(OH)_2^+ + OH^- \leftrightarrow Fe(OH)_{3(aq)}$
CIP_10_FeOH4	$Fe(OH)_2^+ + 2OH^- \leftrightarrow Fe(OH)_4^-$
CIP_11_FeHPO4	$Fe^{3+} + HPO_4^{2-} \leftrightarrow FeHPO_4^+$
CIP_12_FeH2PO4	$Fe^{3+} + H_2PO_4^- \leftrightarrow FeH_2PO_4^{2+}$

3) Physical Mineral Precipitation	
PMP_1_HFO_pre	$Fe(OH)_{3,aq} \leftrightarrow Fe(OH)_{3(s)}$
PMP_2_FePO4	$Fe^{3+} + PO_4^{3-} \leftrightarrow FePO_4$
4) Chemical Surface Complexation	
CSC_01_HFOH_HPO4	adsorption of phosphates onto $X_{HFO,H}$
CSC_02_HFOH_H2PO4	
CSC_03_HFOH_H3PO4	
CSC_04_HFOH_H	Protonation of $X_{HFO,H}$
CSC_05_HFOL_HPO4	adsorption of phosphates onto $X_{HFO,L}$
CSC_06_HFOL_H2PO4	
CSC_07_HFOL_H3PO4	
CSC_08_HFOL_H	Protonation of $X_{HFO,L}$
5) HFO aging processes	
HFO_1_aging_HFOH	$X_{HFO,H} \rightarrow X_{HFO,L}$
HFO_2_aging_HFOL	$X_{HFO,L} \rightarrow X_{HFO,old}$
HFO_3_aging_HFOH,b	$X_{HFO,H,b} \rightarrow X_{HFO,L,b}$
HFO_4_aging_HFOL,b	$X_{HFO,L,b} \rightarrow X_{HFO,old}$

A dynamic physicochemical model for chemical phosphorus removal

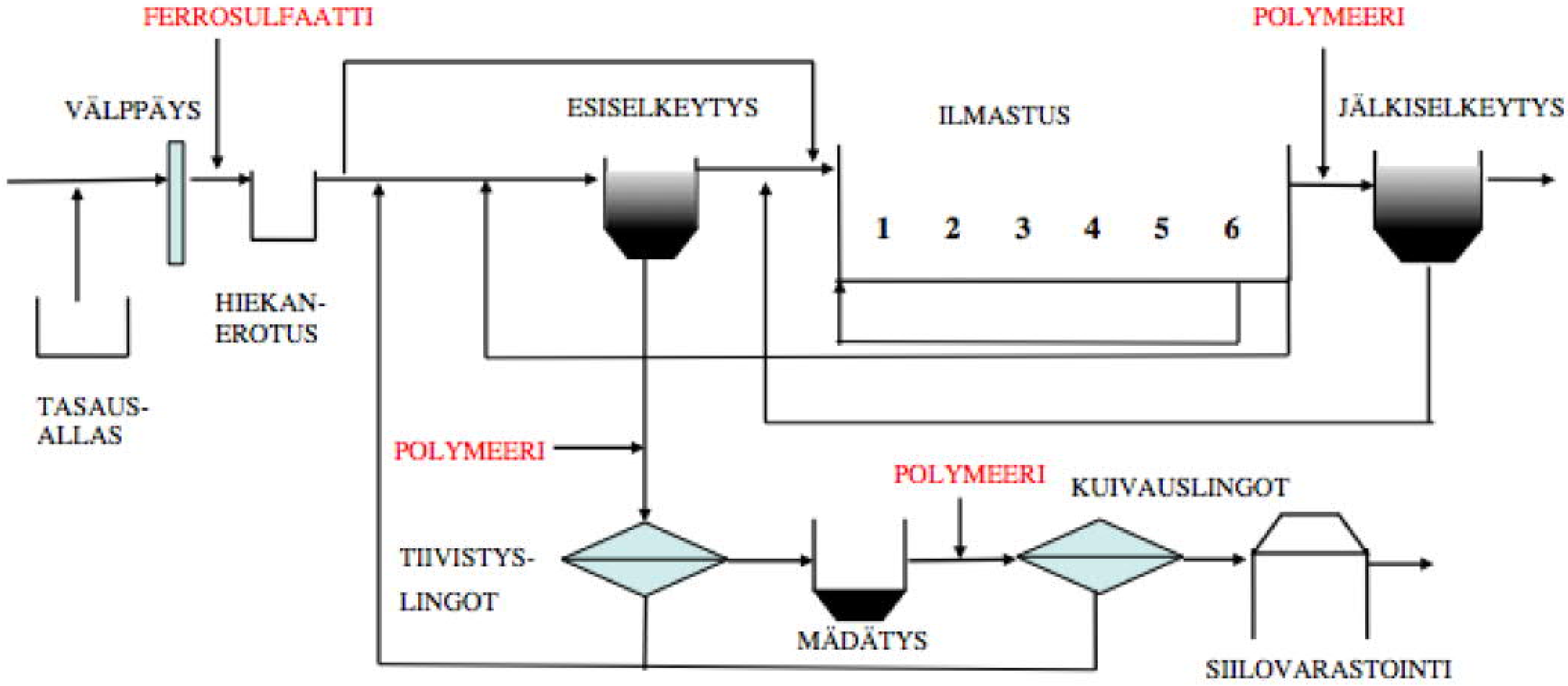
H. Hauduc [a,b,c,*], I. Takács [d], S. Smith [e], A. Szabo [f], S. Murthy [g], G.T. Daigger [h], M. Spérandio [a,b,c]

Excursion to Klaukkala WWTP

Aalto University
School of Engineering

Klaukkala WWTP

The process



FERROSULFAATTI
POLYMEERI
VÄLPPÄYS
ESISELKEYTYS
ILMASTUS
JÄLKISELKEYTYS
1 2 3 4 5 6
HIEKAN-
EROTUS
TASAUS-
ALLAS
POLYMEERI
POLYMEERI
KUIVAUSLINGOT
TIIVISTYS-
LINGOT
MÄDÄTYS
SIILOVARASTOINTI

Excursion Friday May 3rd

Departure at 8:00!!!

Bus transportation from the WATER BUILDING!!