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BIOMATH
Department of Applied Mathematics, Biometrics and Process Control

# SEWAGE: Characteristics and Treatment

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August 3rd 2000

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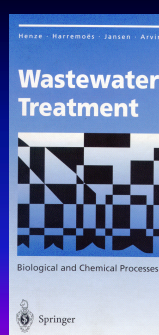
## A good starting point :

Henze et al. (1995)
Wastewater Treatment:
Biological and Chemical Processes
Springer-Verlag, Heidelberg
ISBN 3-540-58816-7






## Sewage: Characteristics

- Flow
- Composition
  - Determinands --> what ?
  - Determinands --> measurement
  - Concentration --> average values
  - Concentration --> dynamic variations

# Sewage: Flow

- Rain
- Infiltration - Exfiltration (leaky sewers !)
- Household wastewater --> 0.2m$^3$/d/PE

PE: Population Equivalent

- Industrial wastewater --> ?




# Sewage Flow: Dry weather

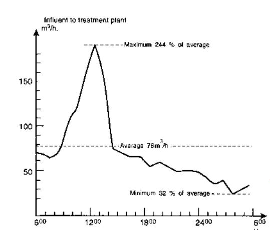


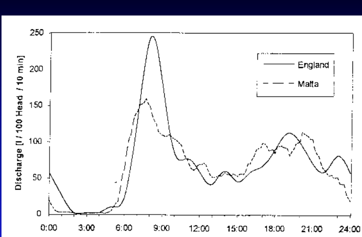

Fig 1.1 *Influent to Tuelsø wastewater treatment plant (Denmark, July 10-11, 1980) /1/.*

x9 !

Diurnal pattern - double sinewave

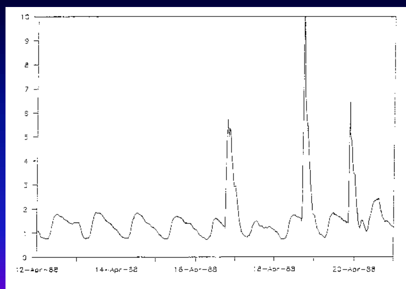



# Sewage Flow: Dry weather




Individual wastewater emission

## Sewage Flow: Wet weather





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## Sewage Flow (cont'd)

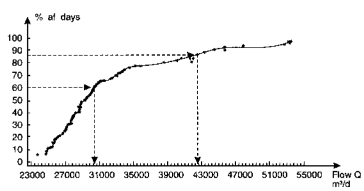


Fig 1.2 *Fractile diagram for influent to Lundtofte wastewater treatment plant 1984-1989 (Denmark). Here $Q_{d,av}$ is determined as the 60%-fractile (30,400 $m^3/d$) and $Q_{d,max}$ as the 85%-fractile (42,500 $m^3/d$). Data from /24/.*

Fractile diagram: Typical way of presenting data !


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## Sewage: Characteristics

- Flow
- Composition
  - Determinands --> what ?
  - Determinands --> measurement
  - Concentration --> average values
  - Concentration --> dynamic variations


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# Sewage composition

| Component | Of special interest | Environmental effect |
|---|---|---|
| Micro-organisms | Pathogenic bacteria, virus and worms eggs | Risk when bathing and eating shellfish |
| Biodegradable organic materials | Oxygen depletion in rivers, lakes and fjords | |
| Other organic materials | Detergents, pesticides, fat, oil and grease, colouring, solvents, phenol, cyanide | Toxic effect, aesthetic inconveniences, bio accumulation |
| Nutrients | Nitrogen, phosphorus, ammonia | Eutrophication, oxygen depletion, toxic effect |
| Metals | Hg, Pb, Cd, Cr, Cu, Ni | Toxic effect, bio accumulation |
| Other inorganic materials | Acids, for example hydrogen sulphide, bases | Corrosion, toxic effect |
| Thermal effects | Hot water | Changing living conditions for flora and fauna |
| Odour (and taste) | Hydrogen sulphide | Aesthetic inconveniences, toxic effect |
| Radioactivity | Toxic effect, accumulation | |

**Table 1.5**
Components in wastewater, partly according to /15/



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# Sewage Composition: Determinands

- Organic pollution
  - $BOD_5$, $BOD_7$, $BOD_\infty$
  - $COD_{tot}$, $COD_s$
  - TOC
  - SS, TSS, Settleables
- Nitrogen pollution
  - $NH_4$-N, $NO_3$-N
  - TKN, TN
- Phosphorous pollution
  - o-$PO_4$
  - TP
- Heavy metals:
  - Hg, Ag,
  - Cd, Zn,
  - Cu, Ni,
  - Pb, As,
  - Cr
- Pathogenic organisms
  - Coliform bacteria
- Specific pollutants
  - LAS detergent (1% !)
  - Phenols



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# Sewage Determinands: BOD

BOD = Biochemical Oxygen Demand

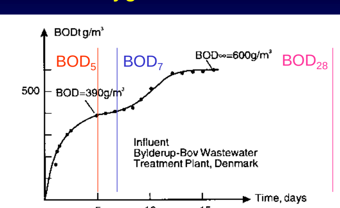


Fig 2.7 *The BODt-curve for mixed municipal and slaughterhouse wastewaters.*

Sewage + few organisms => growth + $O_2$ consumption



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## Sewage Determinands: COD

COD = Chemical oxygen demand

- Chemical oxidation to $CO_2$, $H_2O$, $NH_4$, $SO_4$ at high temperature, very acid
- Amount of oxygen consumed = COD

e.g. 60 g Acetic acid = 64 g COD
$1\ CH_3COOH + 2\ O_2 \rightarrow 2\ CO_2 + 2\ H_2O$

exercise: Ethanol = $CH_3CH_2OH$ Methane = $CH_4$
Sewage = $C_{18}H_{19}O_9N$ Sulphide = $H_2S$
Biomass = $C_5H_7O_2N$
??? How much COD per g organic matter ???



## Sewage Determinands: TOC

TOC = Total Organic Carbon

- Oxidation to $CO_2$ at high temperature / catalytic
- Amount of produced $CO_2$ x 12/44 = TOC

e.g. 60 g Acetic acid = 24 g TOC
$1\ CH_3COOH + 2\ O_2 \rightarrow 2\ CO_2 + 2\ H_2O$



## Sewage Determinands: SS

TSS = Total Suspended Solids

- Dry solids of sample after drying at 105 C = TSS

SS = Suspended Solids

- Dry solids measured after filtering of sample = SS

Settleable Solids

- Dry solids measured after 2 h settling of sample

## Sewage Composition: Dry weather

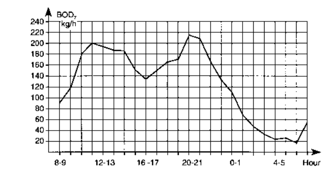



Fig 1.9 *Influent BOD7 (= 1.15 BOD) to Lundtofte wastewater treatment plant (Denmark) /21/.*




## Sewage Composition: Dry weather

- Relative contributions (Butler et al, 1995):
  - WC : 30 - 50 %
  - Bath & Shower : 17 - 28 %
  - Washing Machine : 11 - 31 %
  - Kitchen Sink : 7 - 16 %
  - Washing Basin : 5 - 13 %
- Population Equivalent (Butler et al, 1995):
  - 50.0 g BOD/PE/d
  - 1.4 g o-$PO_4$-P/PE/d
  - 2.3 g $NH_4$-N/PE/d
  - 0.08 g $NO_3$-N/PE/d



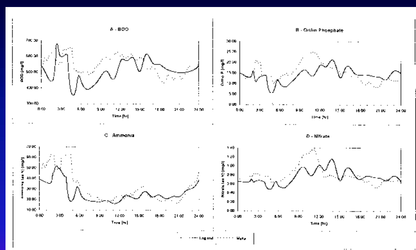

## Sewage Composition: Dry weather

mg pollutant / PE / d (Butler et al., 1995):

| | *WC* | *Kitchen Sink* | *Wash Basin* | *Bath & Shower* | *Washing Machine* | *Total* |
|---|---|---|---|---|---|---|
| **BOD** | 20000 | 10000 | 2000 | 7000 | 11000 | 50000 |
| **o-$PO_4$-P** | 310 | 180 | 385 | 25 | 520 | 1420 |
| **$NO_3$-N** | 22 | 5 | 9 | 10 | 32 | 78 |
| **$NH_4$-N** | 2000 | 55 | 2 | 42 | 170 | 2270 |

Classic number : 54 g BOD / PE / d

## Sewage Composition: Dry weather



Individual wastewater emission



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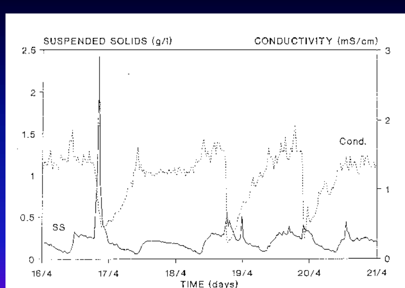
## Sewage Composition: Wet weather




First flush of solids + dilution of dissolved pollutants



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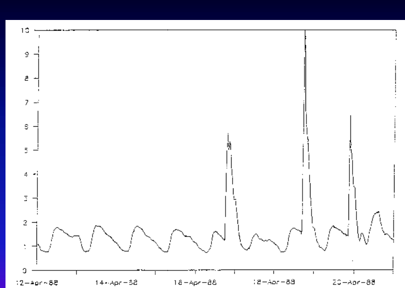
## Sewage Flow: Wet weather





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## Sewage Treatment

- Treatment Principles
  - Biological growth and conversion processes
  - Influences on biological processes
- Treatment Processes
  - COD removal
  - Nitrification
  - Denitrification
  - Phosphate Removal (Biological / Chemical)
  - Anaerobic Digestion



## Sewage treatment: a biological process

A culture of collaborating organisms do the job



## Biological growth

- Growth = multiplication of organisms
- Requirements for growth:
  - nutrients (biomass = $C_5H_7O_2N$, + P, S, ...)
  - favorable environmental conditions (pH, temperature)
- Basic reaction :

  C-source + $NH_4$ + $PO_4$ + $H^+$ ==> Biomass
  + electron acceptor ($O_2$, $NO_3$) + byproducts
  + electron acceptor (C-source) ($H_2O$, $CO_2$, $N_2$, $NO_3$)

## Biological conversion

- Because biomass grows (or at least wants to), a number of compounds are converted, e.g.
  - Organic pollutants --> $CO_2$ + waste biomass
  - $NH_4$ --> $NO_3$
  - $NO_3$ --> $N_2$
  - $PO_4$ --> Poly-P stored in waste biomass
  - Organic pollutants --> biogas ($CH_4$ + $CO_2$)
- How much is converted ?
  - Rate of the conversion reaction ==> KINETICS
  - Ratio of conversions of the different compounds ==> STOICHIOMETRY



## Reaction stoichiometry

Suppose following reaction takes place:

$C_{18}H_{19}O_9N + O_2 + H^+ \to C_5H_7O_2N + CO_2 + H_2O$

for each "molecule" of pollutants degraded, a proportional amount of other products will be used (left of arrow) or produced (right of arrow)

We can therefore write:

$a\ C_{18}H_{19}O_9N + b\ O_2 + c\ H^+ \to d\ C_5H_7O_2N + e\ CO_2 + f\ H_2O$

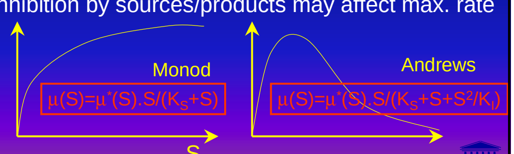
a,b,c,d,e,f are called yield or stoichiometric coefficients

note that one of the coefficients can be chosen = 1



## Process kinetics

- A reaction will not occur (reaction rate = 0) when its sources (substrates) are absent
  - ↳ compounds on the left of the reaction arrow
- A reaction will have a maximum rate
  - when all sources are in excess
  - inhibition by sources/products may affect max. rate



## Conversion rates

Take the conversion above

a $C_{18}H_{19}O_9N$ + b $O_2$ + c $H^+$ --> (1) $C_5H_7O_2N$ + d $CO_2$ + e $H_2O$

Suppose the reaction kinetics: $\mu(S)=\mu^*(S).X.S/(K_S+S)$

- Monod kinetics in the substrate
- first order in the biomass concentration

The conversion of each component is then:

| | | | |
|---|---|---|---|
| $C_{18}H_{19}O_9N$ | : - a. $\mu(S)$ | $C_5H_7O_2N$ | : + 1. $\mu(S)$ |
| $O_2$ | : - b. $\mu(S)$ | $CO_2$ | : + d. $\mu(S)$ |
| $H^+$ | : - c. $\mu(S)$ | $H_2O$ | : + e. $\mu(S)$ |



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## Conversion rates (cont'd)

- Conversion rate of a compound consists of 3 parts:
  - sign (+/-) dependent on whether it is used or produced
  - stoichiometric coefficient in the reaction
  - rate of the reaction
- What if parallel reactions with same compounds ?

  a $C_{18}H_{19}O_9N$ + b $O_2$ + c $H^+$ --> 1 $C_5H_7O_2N$ + d $CO_2$ + e $H_2O$

  f $CO_2$ + g $O_2$ + h $NH_4^+$ --> 1 $C_5H_7O_2N$ + i $NO_3$ + j $H_2O$ + j $H^+$
- ==> $C_5H_7O_2N$, $O_2$, $CO_2$, $H^+$, $H_2O$ occur more than once

| | | | |
|---|---|---|---|
| $C_5H_7O_2N$ | : + 1. $\mu_1$ + 1. $\mu_2$ | $O_2$ | : - b. $\mu_1$ - g. $\mu_2$ |
| $CO_2$ | : + d. $\mu_1$ - f. $\mu_2$ | $H^+$ | : - c. $\mu_1$ + j. $\mu_2$ |



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## General conversion model

- For the i-th compound, $S_i$:

$$r(S_i) = \Sigma_j \text{ sign}(ji)\ v_{ji}.\rho_j$$

where

$\rho_j$ = the rate of the j-th reaction in which $S_i$ participates

$v_{ji}$ = the stoichiometric coefficient for $S_i$ in the j-th reaction

sign(ji) = sign (+/-) indicating whether $S_i$ is substrate or product in the j-th reaction



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## Temperature effect on conversion rate

$\mu(T)=\mu(20).e^{k(T-20)}$

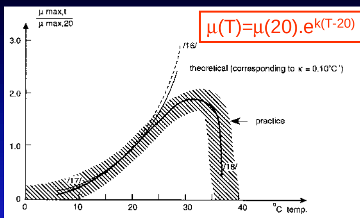



Fig 3.7 *Nitrification as a function of temperature. As opposed to the other biological processes in wastewater treatment, thermophilic nitrifying bacteria are unknown.*

Rule of thumb: Doubling of reaction rate for temperature increase with 10ºC



## Yearly temperature evolution

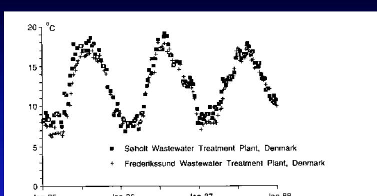


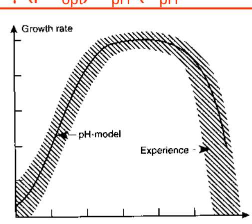

Fig 1.12 *Temperature variation in activated sludge tanks, Søholt and Frederikssund wastewater treatment plants (Denmark) /23/.*

Winter period is critical for process performance, especially for nitrification, since this is the slowest



## pH effect on conversion rates

$\mu(pH)= \mu(pH_{opt}).K_{pH}/(K_{pH} -1+10^{| pH-pHopt |})$




Process is changing the system pH by production of $H^+$ (e.g. nitrification, digestion) or $OH^-$ (denitrification)

## Treatment Processes (1)

- Aerobic organic substrate removal
  - in the presence of $O_2$ (aerobic)
  - heterotrophic organisms (i.e. C-source is organic)
  - $C_{18}H_{19}O_9N + O_2 (+ H^+) + NH_4 \rightarrow C_5H_7O_2N + CO_2 + H_2O$
  - high yield (1 g substrate-COD --> 0.4 g biomass-COD)



## Treatment Processes (2)

- Nitrification
  - in the presence of $O_2$ (aerobic)
  - autotrophic organisms (i.e. C-source is inorganic: $CO_2$)
  - $NH_4 + CO_2 + O_2 + \rightarrow C_5H_7O_2N + NO_3 + H_2O + H^+$
  - low yield (0.24 g COD/g N oxidised)
  - slow growth rate
  - highly sensitive to lots of disturbances (pH, T, inhibitors)
  - in fact: two-step process ($NH_4$ -> $NO_2$ -> $NO_3$)



## Treatment Processes (3)

- Denitrification
  - in the absence of $O_2$ (anoxic)
  - in the presence of $NO_3$ and COD
  - heterotrophic organisms
  - $C_{18}H_{19}O_9N + NO_3 + H^+ + NH_4 \rightarrow C_5H_7O_2N + CO_2 + H_2O + N_2$
  - relatively high yield (0.3 g biomass-COD/g COD)
  - performs both nitrogen and COD removal !
  - recuperates $O_2$ invested in nitrification !

## Treatment Processes (4)

- Excess Biological Phosphorus Removal (EBPR)

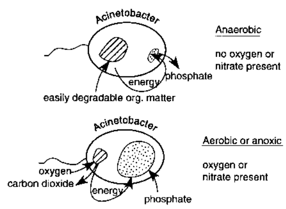



Fig 3.15 *Phosphate transports in and out of bacteria in connection with biological phosphorous removal.*




## Treatment Processes (4)

- Excess Biological Phosphorus Removal (EBPR)
  - requires a sequence of anaerobic (absence of $O_2$ & $NO_3$ ) and (anoxic or) aerobic conditions
  - COD as volatile fatty acids (acetic acid)
  - heterotrophic organisms
  - VFA + $PO_4$ + $NH_4$ + $O_2$ (+$NO_3$) --> $C_5H_7O_2N$ + $CO_2$ + $H_2O$ + Poly-P (+ $N_2$)
  - relatively high yield (0.3 g biomass-COD/g COD)
  - can performs nitrogen, phosphate and COD removal !
  - complex process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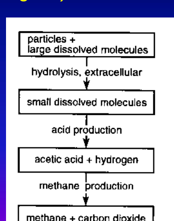
## Treatment Processes (5)

- Anaerobic Digestion
  - consortium of anaerobic organisms (acidogens, methanogens)
  - slow growers
  - delicate balance
    $H_2$ is an inhibitory intermediate
  - $C_{18}H_{19}O_9N$ + $NH_4$ --> $C_5H_7O_2N$ + $CO_2$ + $H_2O$ + $CH_4$

    Biogas





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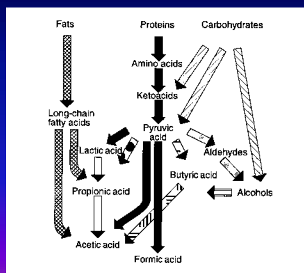
## Treatment Processes (5)

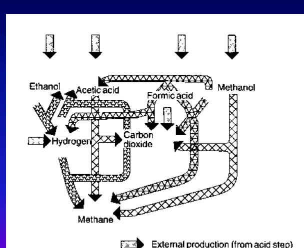
- Anaerobic Digestion: acidification step






## Treatment Processes (5)

- Anaerobic Digestion: methanation step

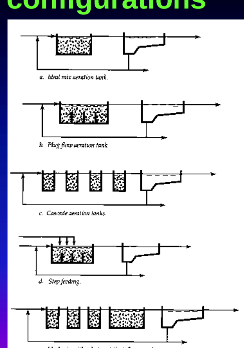




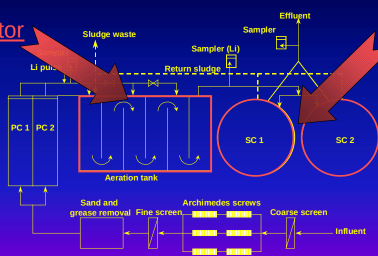

## Typical ASP configurations

Only aerobic reactors

==> only aerobic COD removal
+ nitrification
(if biomass retention is sufficiently long)



# Typical layout of activated sludge system for nitrification only



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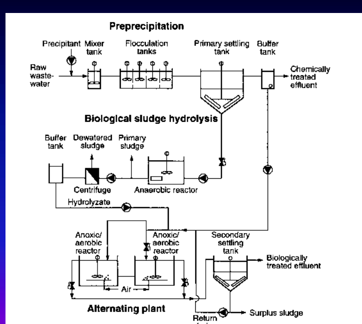
# Typical layout of N/P-removal ASP



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# Biofilm reactors

An increasingly popular alternative for ASP



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## Why growth in flocs / biofilms ?

If the residence time of organisms in the process
<
inverse of their growth rate

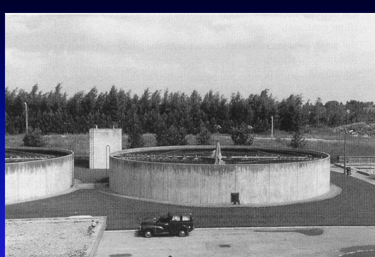
WASH OUT

By growing in
- flocs that settle in the clarifier
- biofilms that attach to surfaces

they can stay sufficiently long in the system



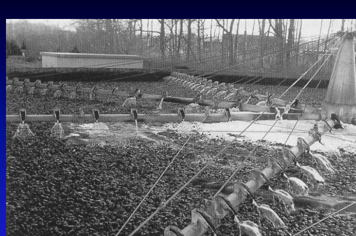
## Trickling Filters



Simple, reasonably performing,
old technology



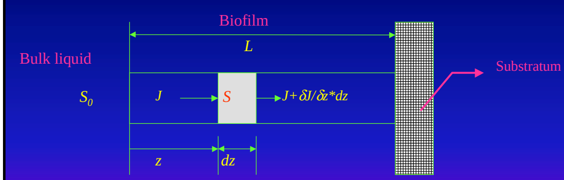
## Trickling Filters



Disadvantages: Clogging + flies
Advantages: Cheap aeration

# Biofilm processes

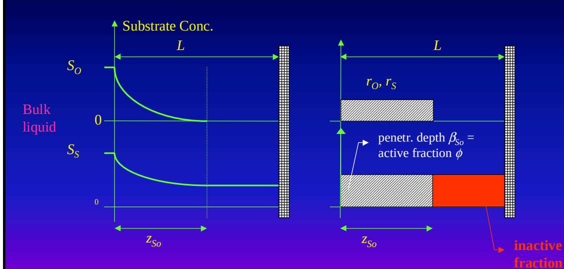
- Conversion + DIFFUSION
  Principle:






# Biofilm processes

Active fraction concept

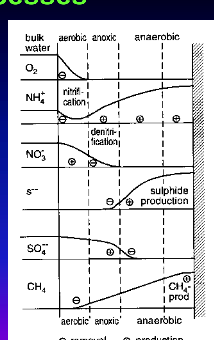





# Biofilm Processes

The active fraction concept: leads to the interpretation of biofilms as systems in which layers exist with different conversion processes taking place

The layers change in size as the process conditions change



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Department of Applied Mathematics, Biometrics and Process Control

# Sewage Treatment: Modelling Hydraulics / Mixing

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3rd-Aug-2000

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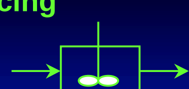
## Overview

- Modelling Environmental Systems: BIOMATH view
- Sewage
  - Characteristics
  - Treatment Principles
  - Treatment Processes
- Modelling
  - Overall approach: Mass balancing
  - Hydraulics/Mixing in Treatment Processes
  - Conversion process modelling
  - Sedimentation models
- Interaction with Sewers / Receiving Waters



## Overall modelling principle: Mass Balancing

Mass Balance for compound:



$$\frac{dM}{dt} = \frac{d(VC)}{dt} = Q_{in}C_{in} - Q_{out}C_{out} + rV$$

transport conversion

with M: Mass of compound in system (g)
C: Concentration of compound (g/m$^3$)
V: Volume of system (m$^3$)
Q: flow rate (m$^3$/h)
r: volumetric conversion rate (g/m$^3$.h)

## Flow Propagation in WWTP

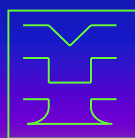
- Normally not considered in detail

$$Q_{out}(t) = Q_{in}(t)$$

- If considered
  - hydraulic package used (Hydroworks, …)
  - Variable volume tanks:

$$\frac{dV}{dt} = Q_{in} - Q_{out}$$
$$Q_{out} = f(V)$$

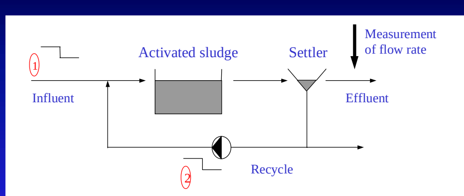
with $f(V) = \alpha\,(V - V_{min})^{\beta}$



$\beta$=1 -> 2



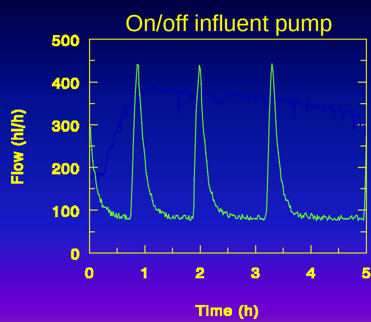
## Example of flow propagation with Variable Volume Tank approach






## Example of flow propagation with Variable Volume Tank approach

# Example of flow propagation






# Modelling of mixing behaviour

- Physically: Dispersion

  "D" in PDE model: $$\frac{\partial C}{\partial t} = U(x)\frac{\partial C}{\partial x} + D\frac{\partial^2 C}{\partial x^2} + \rho$$

- WWT models: "Finite difference" approximation :

  tanks in series approach:

  $$\frac{dV_k C_k}{dt} = Q_k\left(C_{k-1} - C_k\right) + \rho_k V_k \qquad k=1,..,N$$

  Number of tanks in series ≈ modelled dispersion



# Determination of number of tanks

- Empirical equation (Chambers & Thomas, 1985)

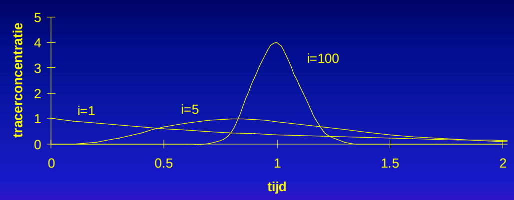
  $$N = \frac{7.4}{W\,H} L\, Q_{in}(1+r)$$

  where
  L = length aeration tank (m)
  W = width aeration tank (m)
  H = depth aeration tank (m)
  $Q_{in}$ = average influent flow rate ($m^3/s$)
  r = recycle ratio (-)

- Experimental evaluation : Inert tracer tests

## The classic Levenspiel figures ...

Response on pulse injection of tracer




No recycle !

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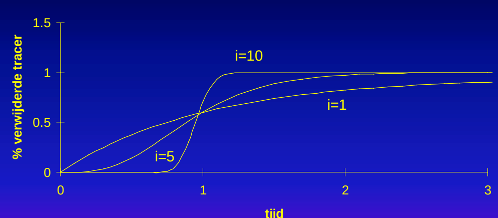
## The classic Levenspiel figures ...

Response on step injection of tracer




No recycle !

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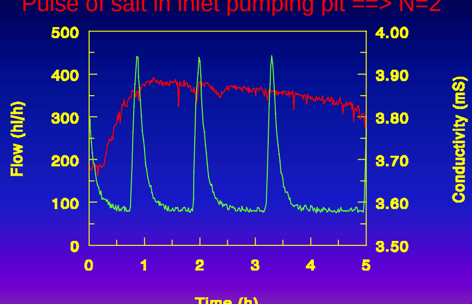
## Examples of tracer tests (1)

Pulse of salt in inlet pumping pit ==> N=2

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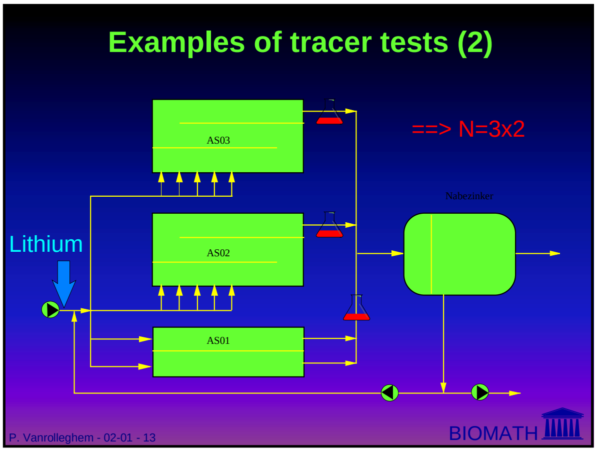
Examples of tracer tests (2)
==> N=3x2
AS03
Nabezinker
Lithium
AS02
AS01
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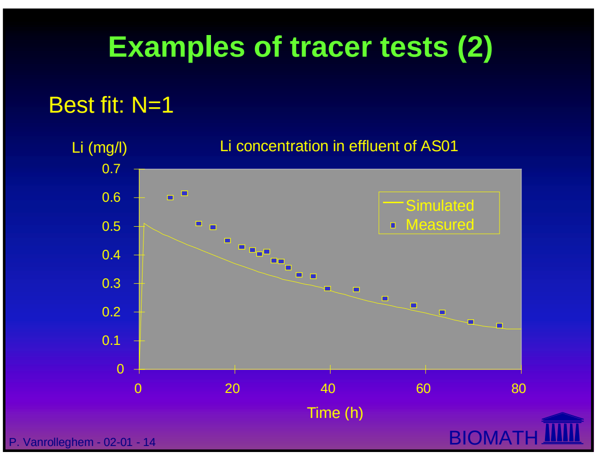
Examples of tracer tests (2)
Best fit: N=1
Li (mg/l)
Li concentration in effluent of AS01
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Simulated
Measured
0
20
40
60
80
Time (h)
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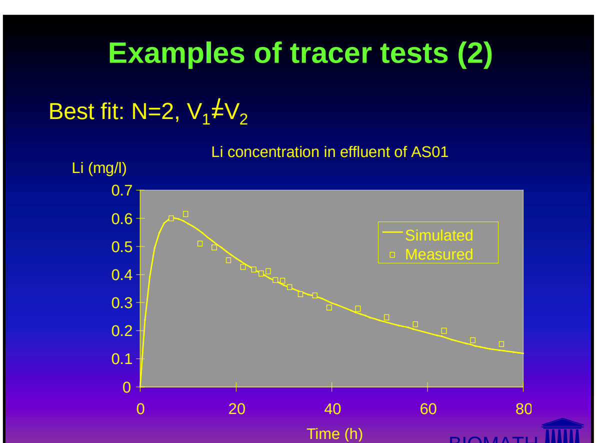
Examples of tracer tests (2)
Best fit: N=2, $V_1 \neq V_2$
Li concentration in effluent of AS01
Li (mg/l)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Simulated
Measured
0
20
40
60
80
Time (h)
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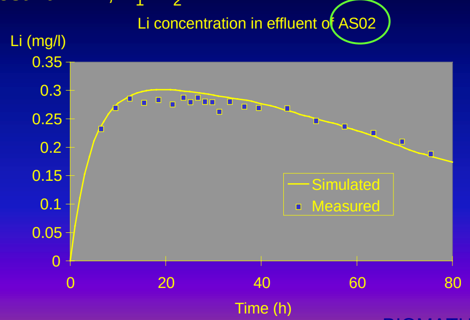
## Examples of tracer tests (2)

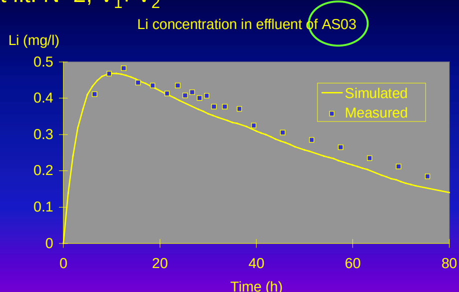
Best fit: N=2, $V_1 \neq V_2$





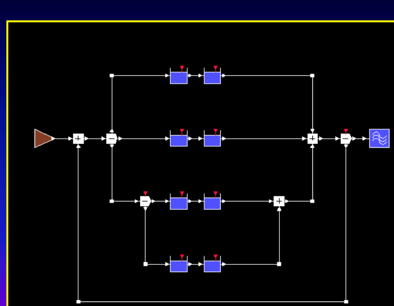

## Examples of tracer tests (2)

Best fit: N=2, $V_1 \neq V_2$



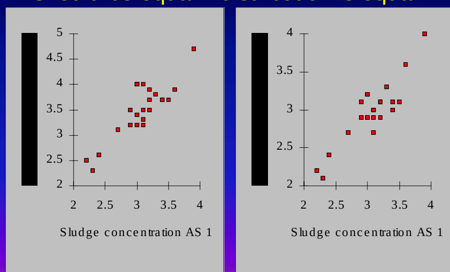



## Implementation in WEST simulator



## Other information regarding mixing !

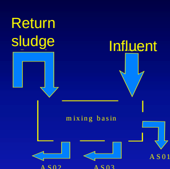
Sludge concentrations in different tanks should be equal if distribution is equal !






## Non-ideal flow distribution

- Distribution box layout

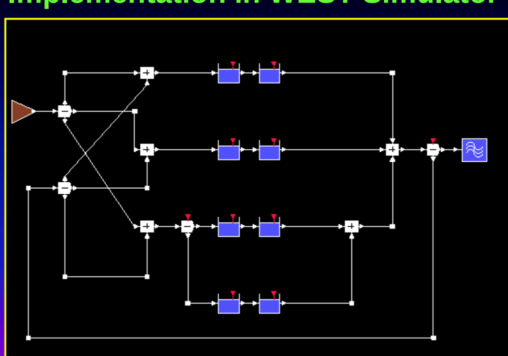



- Short-circuiting leads to unequal loading of tanks !

| | AS01 | AS02 | AS03 |
|---|---|---|---|
| influent fractions $f_{in}$ | 0.36 | 0.24 | 0.4 |
| sludge fractions $f_{sl}$ | 0.345 | 0.31 | 0.345 |

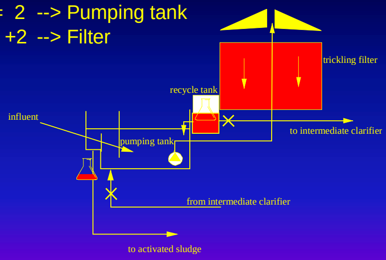


## Implementation in WEST Simulator



# Examples of tracer tests (3)

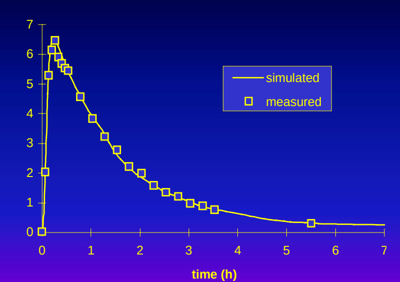
- Trickling Filter:
  - N= 2 --> Pumping tank
  - +2 --> Filter






# Examples of tracer tests (3)

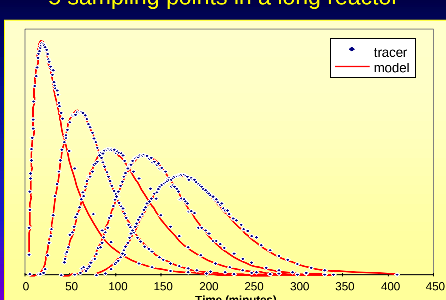
**concentration of Li (ppm) in the effluent**





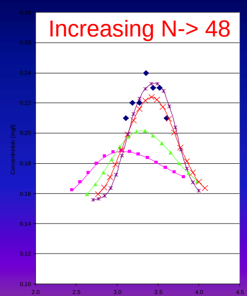

# Example of tracer tests (4)

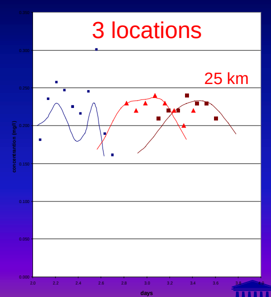
5 sampling points in a long reactor



## Example of tracer test in river Lambro

Measurement of daily wastewater bypass (boron)






## Experimental design of tracer test

- Choose an inert substance:
  - not biodegradable
  - not adsorbing
  - Lithium, Rhodamine, Salt
- Data collection:
  - Period: over 3 times the hydraulic retention time
  - Frequency: take 20-50 samples
- Recycle => Numerical fitting of mixing model to data
- Non-equal volume approach mostly necessary for adequate description of mixing behaviour
- Additional data (MLSS) can provide further info



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# Sewage Treatment: Modelling Hydraulics / Mixing

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3rd-Aug-2000

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# Sewage Treatment: Conversion Process Modelling

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## Overview

- Modelling Environmental Systems: BIOMATH view
- Sewage
  - Characteristics
  - Treatment Principles
  - Treatment Processes
- Modelling
  - Overall approach: Mass balancing
  - Hydraulics/Mixing in Treatment Processes
  - Conversion process modelling
  - Sedimentation models
- Interaction with Sewers / Receiving Waters



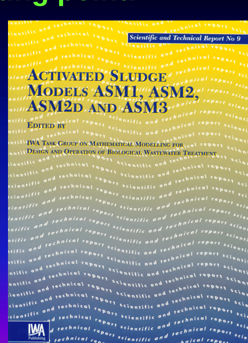
## "The" starting point:

Henze, M., Gujer, W., Takashi, M. and van Loosdrecht, M. (2000)

Activated Sludge Models ASM1, ASM2, ASM2D and ASM3.

Scientific and Technical Report No. 9

IWA Publishing, London.



## Peterson (1965) matrix notation

Components, Processes, Stoichiometry & Kinetics:

Continuity →; ↓ Mass Balance

| Component → $i$ / $j$ Process ↓ | 1 $X_B$ | 2 $S_S$ | 3 $S_O$ | Process Rate, $\rho_j$ $[ML^{-3}T^{-1}]$ |
| --- | --- | --- | --- | --- |
| 1 Growth | 1 | $-\frac{1}{Y}$ | $-\frac{1-Y}{Y}$ | $\frac{\hat{\mu} S_S}{K_S + S_S} X_B$ |
| 2 Decay | $-1$ | | $-1$ | $b X_B$ |
| Observed Conversion Rates $ML^{-3}T^{-1}$ | $r_i = \sum_j r_{ij} = \sum_j \nu_{ij} \rho_j$ | | | Kinetic Parameters: Maximum specific growth rate: $\hat{\mu}$; Half-velocity constant: $K_S$; Specific decay rate: $b$ |
| Stoichiometric Parameters: True growth yield: Y | Biomass $[M(COD)\,L^{-3}]$ | Substrate $[M(COD)\,L^{-3}]$ | Oxygen (negative COD) $[M(-COD)\,L^{-3}]$ | |



## Mass balancing

- Vertical summation of

  Stoichiometry term * Kinetics

  terms gives total conversion

$$r(S_i) = \Sigma_j \text{ sign}(ji)\ v_{ji}.\rho_j$$

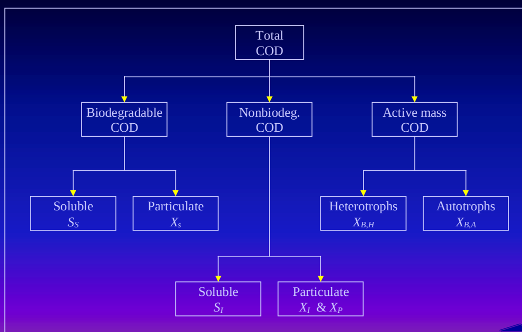
Add the transport terms ==> the mass balance !



## Activated Sludge Model No 1

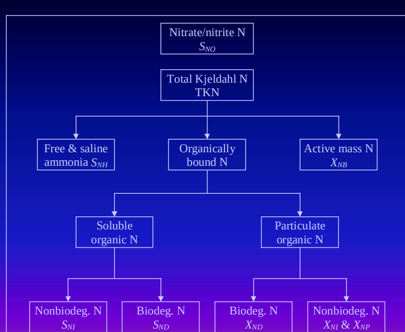
- Henze et al. (1987)
- Innovations:
  - Nomenclature: Solubles: symbol S; Particulates: symbol X
  - Focus on:
    - Sludge production
    - Oxygen consumption
    - Nitrogen removal
  - COD based modelling ==> Mass balancing
  - Peterson matrix

## ASM1: COD-components






## ASM1: N-components

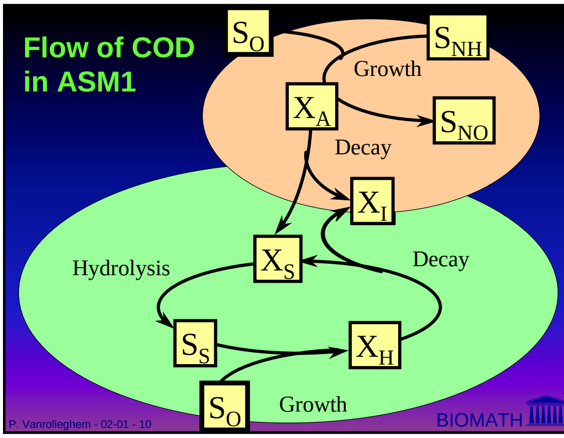





## ASM1: Processes

1) Growth of biomass
   - heterotrophs
     - aerobic
     - anoxic
   - autotrophs (nitrification)
2) Decay of biomass
   - heterotrophs
   - autotrophs
3) Ammonification of organic nitrogen
4) Hydrolysis of particulate organic matter

## Flow of COD in ASM1

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## ASM1: Peterson matrix

| Component (i) → ↓ Process (j) | 1 $S_I$ | 2 $S_S$ | 3 $X_I$ | 4 $X_S$ | 5 $X_{BH}$ | 6 $X_{BA}$ | 7 $X_P$ | 8 $S_O$ | 9 $S_{NO}$ | 10 $S_{NH}$ | 11 $S_{ND}$ | 12 $X_{ND}$ | 13 $S_{ALK}$ | Process rate ($\rho_j$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 Aerobic growth of heterotrophic biomass | | $-\frac{1}{Y_H}$ | | | 1 | | | $-\frac{1-Y_H}{Y_H}$ | | $-i_{XB}$ | | | $-\frac{i_{XB}}{14}$ | $\mu_{max\,H}\frac{S_S}{K_S+S_S}\frac{S_O}{K_{OH}+S_O}X_{BH}$ |
| 2 Anoxic growth of heterotrophic biomass | | $-\frac{1}{Y_H}$ | | | 1 | | | | | $-i_{XB}$ | | | $\frac{1-Y_H}{14\cdot 2.86Y_H}$ $-\frac{i_{XB}}{14}$ | $\eta_g\mu_{max\,H}\frac{S_S}{K_S+S_S}\frac{K_{OH}}{K_{OH}+S_O}\frac{S_{NO}}{K_{NO}+S_{NO}}X_{BH}$ |
| 3 Aerobic growth of autotrophic biomass | | | | | | 1 | | $-\frac{4.57-Y_A}{Y_A}$ | $\frac{1}{Y_A}$ | $-i_{XB}-\frac{1}{Y_A}$ | | | $-\frac{i_{XB}}{14}-\frac{1}{7Y_A}$ | $\mu_{max\,A}\frac{S_{NH}}{K_{NH}+S_{NH}}\frac{S_O}{K_{OA}+S_O}X_{BA}$ |
| 4 Decay of heterotrophic biomass | | | | $1-f_P$ | $-1$ | | $f_P$ | | | | | $i_{XB}-f_P i_{X}$ | | $b_H X_{BH}$ |
| 5 Decay of autotrophic biomass | | | | $1-f_P$ | | $-1$ | $f_P$ | | | | | $i_{XB}-f_P i_{X}$ | | $b_A X_{BA}$ |
| 6 Ammonification of soluble organic nitrogen | | | | | | | | | | 1 | $-1$ | | 1/14 | $k_a S_{ND} X_{BH}$ |
| 7 Hydrolysis of slowly biodegradable substrate | | 1 | | $-1$ | | | | | | | | | | $k_h\frac{X_S/X_{BH}}{K_X+X_S/X_{BH}}\left[\frac{S_O}{K_{OH}+S_O}+\eta_h\frac{K_{OH}}{K_{OH}+S_O}\frac{S_{NO}}{K_{NO}+S_{NO}}\right]X_{BH}$ |
| 8 Hydrolysis of organic nitrogen | | | | | | | | | | | 1 | $-1$ | | $\rho_7(X_{ND}/X_S)$ |

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## Continuity check

- Horizontal summation of stoichiometric coefficients should equal 0 !

$$\Sigma_i\, v_{ji}.i_{ci} = 0$$

Provided: - consistent units have been used
- all substrates/products are included

This can be done for COD, N, P, Charge, Mass

--> Example: ASM3 !

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| j | Component i > | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Process | $S_O$ | $S_I$ | $S_S$ | $S_{NH}$ | $S_{N2}$ | $S_{NO}$ | $S_{HCO}$ | $X_I$ | $X_S$ | $X_H$ | $X_{STO}$ | $X_A$ | $X_{TS}$ |
| v | expressed as > | $O_2$ | COD | COD | N | N | N | Mole | COD | COD | COD | COD | COD | TSS |
| 1 | Hydrolysis | | $f_{SI}$ | $1-f_{SI}$ | $y_1$ | | | $z_1$ | | -1 | | | | $-i_{XS}$ |
| Heterotrophic organisms, denitrification | | | | | | | | | | | | | | |
| 2 | Aerobic storage of COD | $x_2$ | | -1 | $y_2$ | | | $z_2$ | | | | $Y_{STO}$ | | $t_2$ |
| 3 | Anoxic storage of COD | | | -1 | $y_3$ | $-x_3$ | $x_3$ | $z_3$ | | | | $Y_{STO}$ | | $t_3$ |
| 4 | Aerobic growth | $x_4$ | | | $y_4$ | | | $z_4$ | | | 1 | $-1/Y_H$ | | $t_4$ |
| 5 | Anoxic growth (denitrification) | | | | $-i_{NBM}$ | $-x_5$ | $x_5$ | $z_5$ | | | 1 | $-1/Y_H$ | | $t_5$ |
| 6 | Aerobic endog. respiration | $-(1-f_I)$ | | | $y_6$ | | | $z_6$ | $f_I$ | | -1 | | | $t_6$ |
| 7 | Anoxic endog. respiration | | | | $y_6$ | $-x_7$ | $x_7$ | $z_7$ | $f_I$ | | -1 | | | $t_7$ |
| 8 | Aerobic respiration of PHA | -1 | | | | | | | | | | -1 | | -0.60 |
| 9 | Anoxic respiration of PHA | | | | | $-x_9$ | $x_9$ | $z_9$ | | | | -1 | | -0.60 |
| Autotrophic organisms, nitrification | | | | | | | | | | | | | | |
| 10 | Nitrification | $x_8$ | | | $y_{10}$ | | $1/Y_A$ | $z_{10}$ | | | | | 1 | $i_{TSBM}$ |
| 11 | Aerobic endog. respiration | $-(1-f_I)$ | | | $y_{11}$ | | | $z_{11}$ | $f_I$ | | | | -1 | $t_{11}$ |
| 12 | Anoxic endog. respiration | | | | $y_{12}$ | $-y_{12}$ | $y_{12}$ | $z_{12}$ | $f_I$ | | | | -1 | $t_{12}$ |
| Composition matrix $\iota_{k,I}$ | | | | | | | | | | | | | | |
| k | Conservatives | | | | | | | | | | | | | |
| 1 | COD g COD | -1 | 1 | 1 | | -1.71 | -4.57 | | 1 | 1 | 1 | 1 | 1 | |
| 2 | Nitrogen g N | | $i_{NSI}$ | $i_{NSS}$ | 1 | 1 | 1 | | $i_{NXI}$ | $i_{NXS}$ | $i_{NBM}$ | | $i_{NBM}$ | |
| 3 | Ionic charge Mole + | | | | 1/14 | | -1/14 | -1 | | | | | | |
| | Observables | | | | | | | | | | | | | |
| 4 | TSS g TSS | | | | | | | | $i_{TSXI}$ | $i_{TSXS}$ | $i_{TSBM}$ | 0.60 | $i_{TSBM}$ | |

# ASM3 Composition matrix Solubles

| | Component | $S_O$ | $S_I$ | $S_S$ | $S_{NH}$ | $S_{N2}$ | $S_{NO}$ | $S_{HCO}$ |
|---|---|---|---|---|---|---|---|---|
| | expressed as > | $O_2$ | COD | COD | N | N | N | Mole |
| Composition matrix $\iota_{k,i}$ | | | | | | | | |
| k | Conservatives | | | | | | | |
| 1 | COD g COD | -1 | 1 | 1 | | -1.71 | -4.57 | |
| 2 | Nitrogen g N | | $i_{NSI}$ | $i_{NSS}$ | 1 | 1 | 1 | |
| 3 | Ionic charge Mole + | | | | 1/14 | | -1/14 | -1 |
| | Observables | | | | | | | |
| 4 | TSS g TSS | | | | | | | |



# ASM3 Composition matrix Particulates

| | Component | $X_I$ | $X_S$ | $X_H$ | $X_{STO}$ | $X_A$ | $X_{TS}$ |
|---|---|---|---|---|---|---|---|
| | expressed as | COD | COD | COD | COD | COD | TSS |
| Composition matrix $\iota_{k,i}$ | | | | | | | |
| k | Conservatives: Conservation equation | | | | | | |
| 1 | COD g COD | 1 | 1 | 1 | 1 | 1 | |
| 2 | Nitrogen g N | $i_{NXI}$ | $i_{NXS}$ | $i_{NBM}$ | | $i_{NBM}$ | |
| 3 | Ionic charge Mole + | | | | | | |
| | Observables: Composition equation | | | | | | |
| 4 | TSS g TSS | $i_{TSXI}$ | $i_{TSXS}$ | $i_{TSBM}$ | 0.60 | $i_{TSBM}$ | |

## Consistency Check ASM3

**Conservation eq.:** $\sum_i \nu_{j,i} \cdot \iota_{k,i} = 0 \quad \text{for} \quad i = 1 \text{ to } 12$

for k = COD, N and ionic charge
yields $j \cdot k = 36$ equations which
allow easily to predict all $\mathbf{x_j}$, $\mathbf{y_j}$, $\mathbf{z_j}$

**TSS Composition equation**

$$t_j = \nu_{j,TSS} = \sum_i \nu_{j,i} \cdot \iota_{TSS,i} \quad \text{for } i = 8 \text{ to } 12$$

yields j = 12 equations which
allow easily to predict all $\mathbf{t_j}$



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## Sewage Treatment: Conversion Process Modelling

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# Sedimentation: making the adequate model choice

Bob De Clercq, Diedert Debusscher and Peter A. Vanrolleghem

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## Contents

- Why modelling sedimentation ?
- Model survey (0D-3D)
- Settling velocity functions
- Extensions for special systems
- Sedimentation models: the adequate choice !



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## Why modeling sedimentation ?

- Primary clarification: load, COD/N-ratio
- Sludge balance of activated sludge
- Dynamics of sludge motion between settler/AST
- Effluent quality (SS, Sludge blanket)
- Control systems
- Sludge production (thickening)
- Design of settler structures, e.g. baffles



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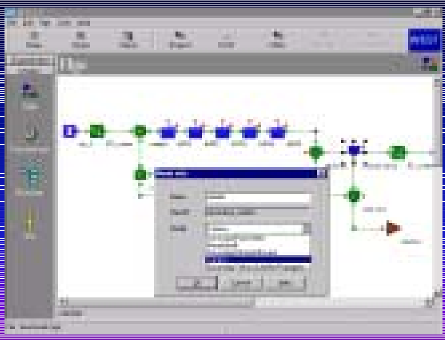
## Choosing the adequate model ?





## Model survey

- Settler models are classified according their spatial detail :
  - 0D (point settler)
  - 1D (homogeneous in x- and y-direction)
  - 2D (homogeneous in y-direction)
  - 3D (non-homogeneous)
- Model = spatial description + settling properties
  settling velocity function
- Sometimes reactions too: denitrification / hydrolysis



## 0D-Models

- Point settler = ideal separator without volume

mass conservation :

$$Q_f X_f f_{ns} = Q_{eff} X_{eff}$$

$$Q_f X_f (1 - f_{ns}) = Q_u X_u$$

sometimes $f_{ns}$ as an increasing function of flow rate (≈ turbulence)

- Problem: no residence time !

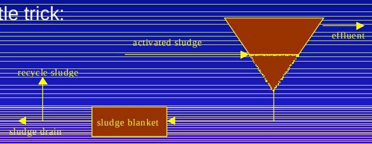
## 0D-Models

- Point settler with volume (sludge retention): n CSTR's

  $dM_X/dt = Q_f X_f - Q_{eff} X_{eff} - Q_u X_u$

- Point settler + reactor with volume and conversion

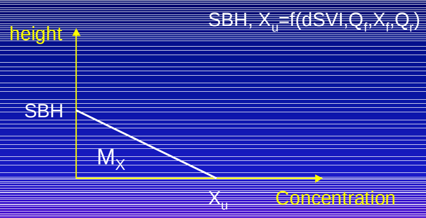
  little trick:






## 1/2D-Models

- EAWAG-model (Siegrist et al., 1995)




+ mass balance: $dM_X/dt = Q_f X_f - Q_{eff} X_{eff} - Q_u X_u$



## 1D-Models

- Discretisation with finite differences of the PDE :

$$\frac{\partial X}{\partial t} = \frac{\partial (D \partial X)}{\partial z^2} - \frac{\partial (vX)}{\partial z} - RX$$

assumptions :

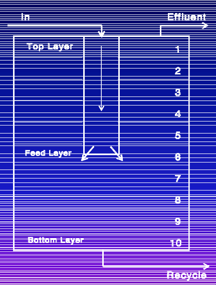
X uniform in horizontal plane ;

no vertical dispersion (D=0) ;

no biological reaction (R=0) ;

Discretisation:

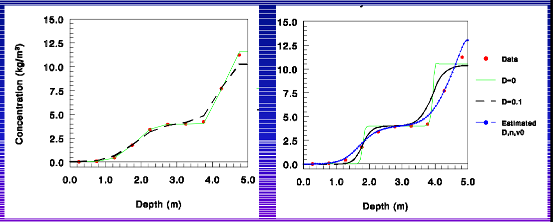
$\partial X / \partial z = X(j)-X(j+1)/h$



## 1D-models with dispersion

$$\frac{\partial X}{\partial t} = \frac{\partial (D \partial X)}{\partial z^2} - \frac{\partial (vX)}{\partial z} - RX \qquad D(z,Q_f)$$

10-layer model — model with dispersion




So: Equivalent ! Number of layers = 1/D !



## 2D- & 3D-Models

- Mass balance: $\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0$
- Momentum equation:

$$\frac{\partial U}{\partial t} + \frac{\partial U^2}{\partial x} + \frac{\partial UV}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\nu_{eff}\frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{eff}\frac{\partial U}{\partial y}\right)$$

$$\frac{\partial V}{\partial t} + \frac{\partial UV}{\partial x} + \frac{\partial V^2}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\nu_{eff}\frac{\partial V}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{eff}\frac{\partial V}{\partial y}\right) + g\frac{\rho - \rho_w}{\rho_w}$$

with: $\nu_{eff} = \nu + \nu_t \qquad \nu_t = c_\mu \frac{k^2}{\varepsilon}$



## 2D- & 3D-Models

- Density

$$\rho = \rho_r + X\left(1 - \frac{\rho_r}{\rho_s}\right)$$

- Transport equation for particles concentration

$$\frac{\partial X}{\partial t} + \frac{\partial UX_i}{\partial x} + \frac{\partial (V - V_{si})X}{\partial y} = \frac{\partial}{\partial x}\left(\frac{\nu_{eff}}{\sigma_c}\frac{\partial X_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\nu_{eff}}{\sigma_c}\frac{\partial X_i}{\partial y}\right)$$

## 2D- & 3D-Models

- Turbulence model (k - ε)

$$\frac{\partial k}{\partial t}+\frac{\partial Uk}{\partial x}+\frac{\partial Vk}{\partial y}=\frac{\partial}{\partial x}\left(\frac{\nu_{eff}}{\sigma_k}\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\nu_{eff}}{\sigma_k}\frac{\partial k}{\partial y}\right)+P_r+P_g-\varepsilon$$

$$\frac{\partial \varepsilon}{\partial t}+\frac{\partial U\varepsilon}{\partial x}+\frac{\partial V\varepsilon}{\partial y}=\frac{\partial}{\partial x}\left(\frac{\nu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\nu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right)+c_1\frac{\varepsilon}{k}P_r-c_2\frac{\varepsilon^2}{k}$$

with: $$P_r = \nu_{eff}\left[2\left(\frac{\partial U}{\partial x}\right)^2+2\left(\frac{\partial V}{\partial y}\right)^2+\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right)^2\right]$$

$$P_g = \frac{g}{\rho_W}\cdot\frac{\nu_{eff}}{\sigma_c}\cdot\frac{\partial(\rho-\rho_W)}{\partial y}$$

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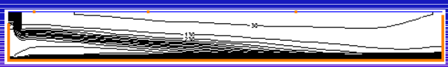
## 2D- & 3D-Models

- Velocity profile:


- Sludge concentration profile



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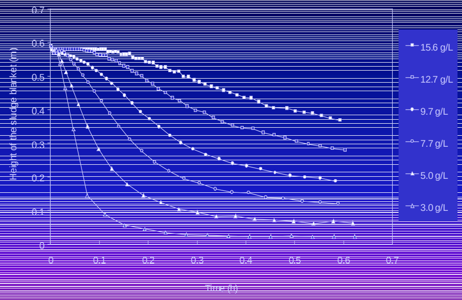
## Settling velocity functions

**$V_s$ decreases with increasing X**

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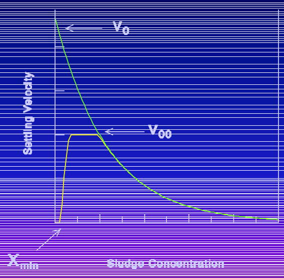
## Settling velocity functions

- Settling velocity $V_s = f(X(x,y,z))$
  $V_s = g(dSVI)$






## Settling velocity functions

- Vesilind (1969): $v_s = k e^{-nX}$
- Dick & Young (1972): $v_s = k' X^{-n'}$
- Cho et al. (1993): $v_s = k'' \dfrac{e^{-n'' X}}{X}$
- Takacs et al. (1991):

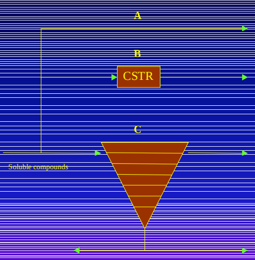
$$v_{sj} = v_0 e^{-r_h (X_j - X_{min})} - v_0 e^{-r_p (X_j - X_{min})}$$

$$\text{with } 0 \le v_{sj} \le v_0'$$



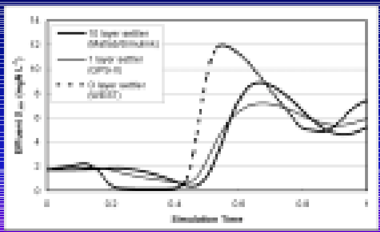
## Possible extensions: soluble compounds

3 approaches:



## Possible extensions: soluble compounds

- Non-negligible effect:



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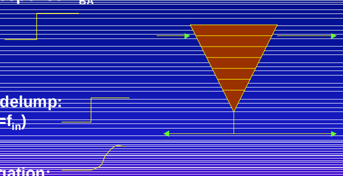
## Possible extensions: biomass propagation

Step response $X_{BA}$



Lump/delump: ($f_{uit}=f_{in}$)

Propagation: $dX_{BA}(j)/dt = ...$

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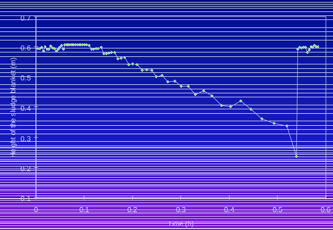
## Possible extensions: biological reactions

- Denitrification (build-up of $N_2$-gas in sludge floc)



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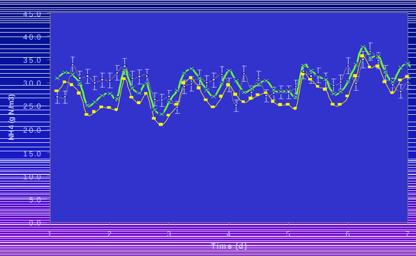
## Possible extensions: biological reactions

- Hydrolysis/ammonification in primary clarifier:



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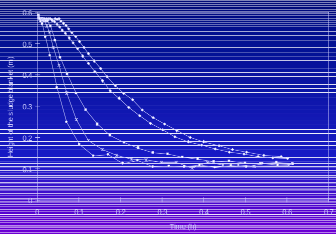
## Possible extensions: flocculants for improved sedimentation

- e.g. effect of polymer:



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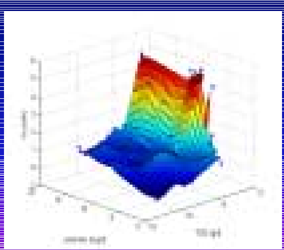
## Possible extensions: flocculants for improved sedimentation

- Description of the polymer effect:



$$Vs = 10.59 e^{\frac{-X}{1.54 * P + 2.5}}$$

Used for prediction of the settler's behavior when polymer is dosed

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## Sedimentation models: making the adequate choice

| Model application | Model complexity |
|---|---|
| Sludge management in activated sludge tanks | 0D coupled models |
| Management sludge storage in settler | 1D coupled and/or 2D coupled models |
| Sludge recirculation | 1D coupled and/or 2D coupled models |
| Sludge blanket height | 1D coupled and/or 2D coupled models |
| Optimisation tank geometry | 2D and/or 3D models |
| Retrofitting (eg. baffles) | 2D and/or 3D models |
| Effluent SS-concentration | Circular basins: 2D ; rectangular basins: 2 and/or 3D |
| Basins exposed to wind forces | 3D models |
| Density currents | at least 2D models |



## Sedimentation models: making the adequate choice

- 0D model: low calculation time
  too low accuracy
- 1/2D model: low calculation time
  acceptable accuracy
- 1D model: acceptable calculation time
  acceptable accuracy
- 2 & 3D model: high calculation time
  excellent accuracy
  only specific applications ($X_{eff}$)