UNIVERSITEIT GENT

BIOMATH

Department of Applied Mathematics, Biometrics and Process Control

THE SEDIFLOC PROJECT

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Why sedifloc ?

- Settling is often still a bottleneck in WWTP
- Improve knowledge of AS flocculation
  - mechanism
  - environmental influences
- Model final clarifier
- Calibrate 1D-model

SBR (80L)
sludge breeding

-STABILITY-

Monitoring:

On-line:
- DO concentration
- pH

Off-line:

Effluent:
- COD
- N_{total}, NO_2-N, NO_3-N, NH_3
- PO_4-P

Sludge
- MLSS, MLVSS, SVI
- DGGE (microbial stability)

Influent
- 7 days stability

Floc Unit (5L)
flocculation experiments

-DYNAMICS-

Monitoring:

On-line:
- DO concentration
- pH
- Conductivity
- Shear stress
- PSD
- Image analysis
- …..

Off-line:
- Settling velocity
- SVI

Flocculation Knowledge ↔ **Population Balance Modelling (PBM)**

2D-Clarifier Modelling

COMPUTATIONAL FLUID DYNAMICS (CFD)

Prediction of velocity, AS-conc. pattern

Virtual Optimal Experimental Design (Virtual OED)

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Sequencing Batch Reactor

Sequencing Batch Reactor

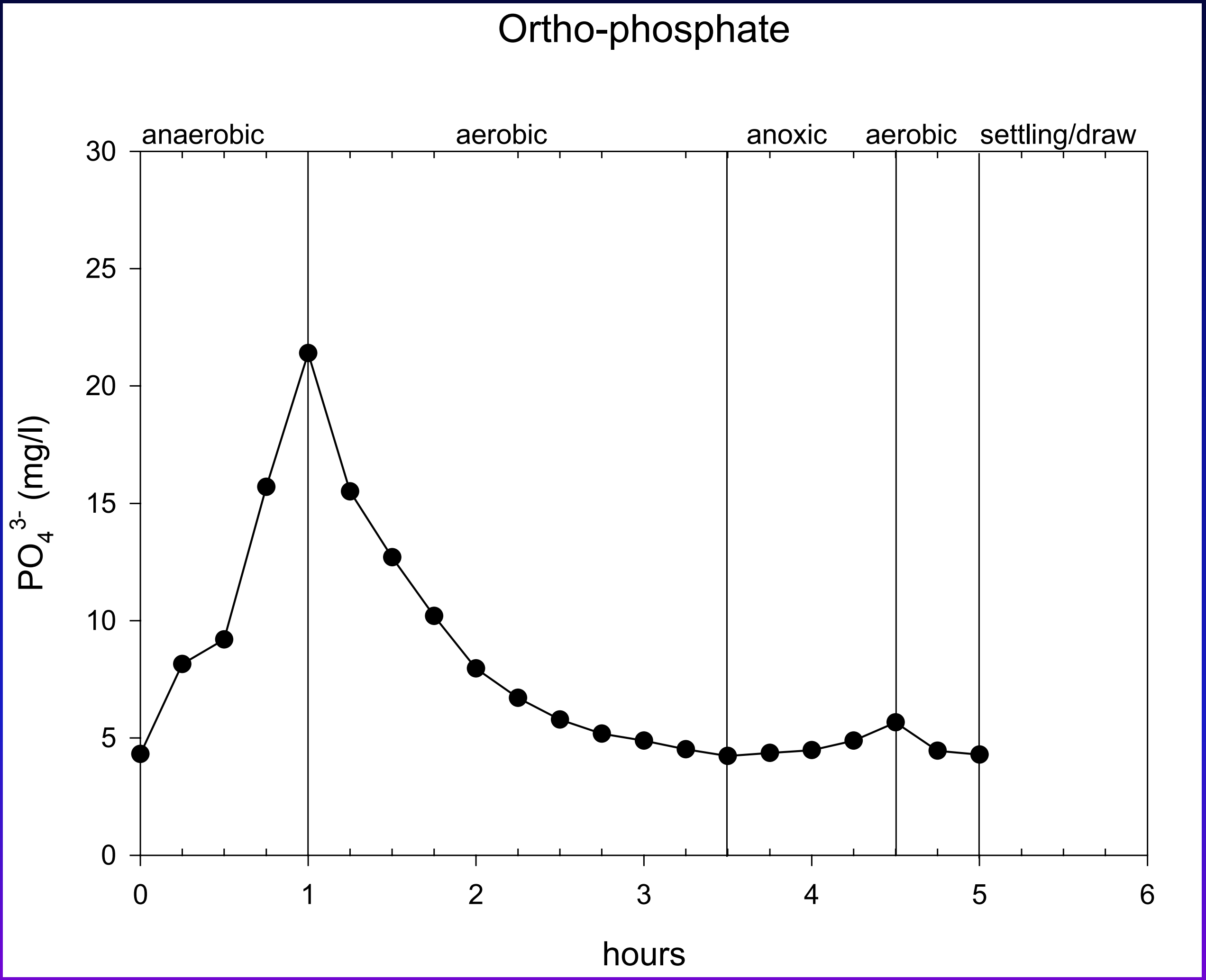
- Aim ⟶ eliminate biological variability

- Characteristics
  - V= 80 l
  - SRT= 10 d
  - HRT = 12h
  - synthetic influent (COD/N/P = 100/13,7/2,14)
- Measurements
  - DO, pH, ORP, conductivity , weight (on-line)
  - COD, CODsol, Total-N, NH_4, NO_3, NO_2, PO_4 (off-line)
  - MLSS (2-3 g/l), SVI (80-120 ml/g)
  - DGGE (microbial community)

SBR (2)

- Performance
  - 95 % COD-removal
  - 65 % N-removal
  - complete nitrification / incomplete denitrification
  - 65 % PO_4-removal

SBR (3)



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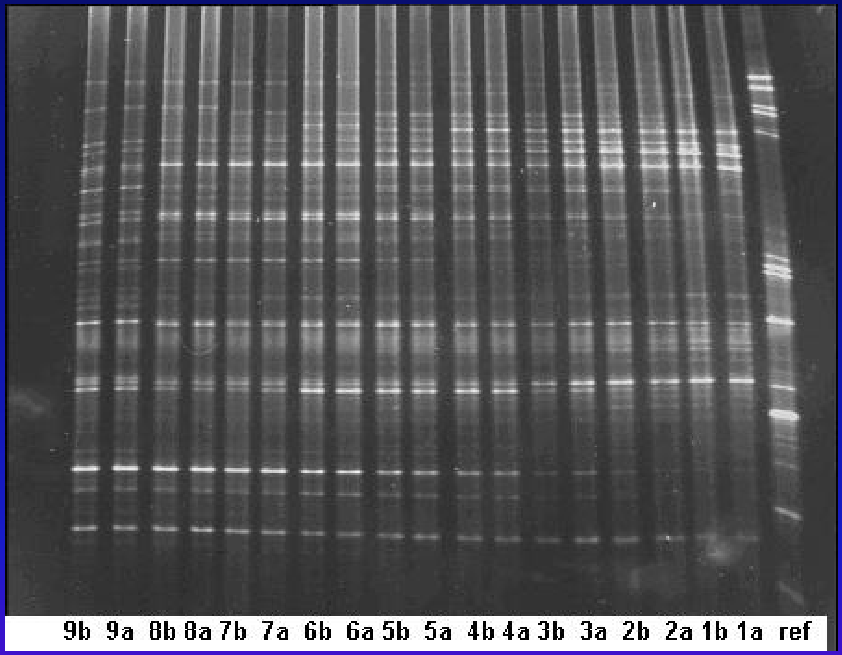
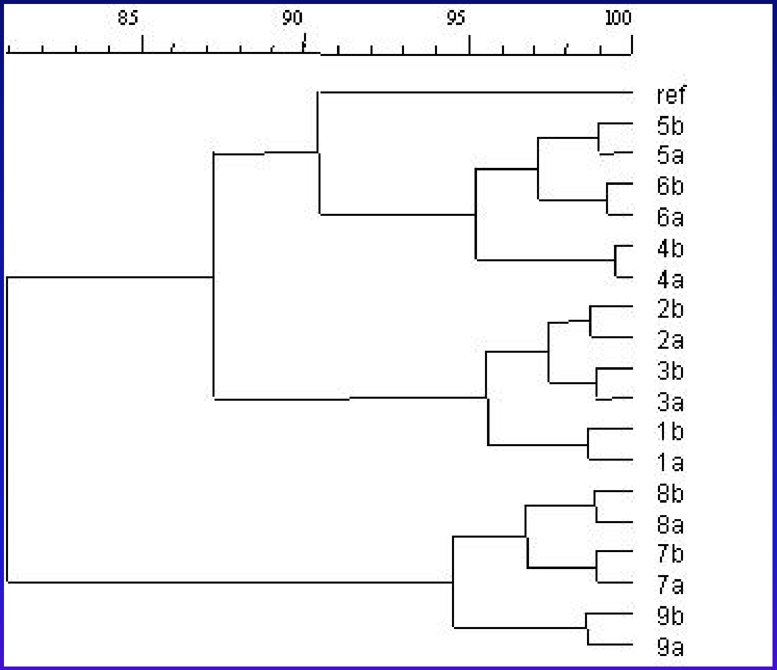
SBR (4)

- DGGE analysis of 16S rRNA genes

  examine temporal differences
  within the activated sludge bacterial community





DGGE profile for replicate samples and cluster analysis

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Floc Unit

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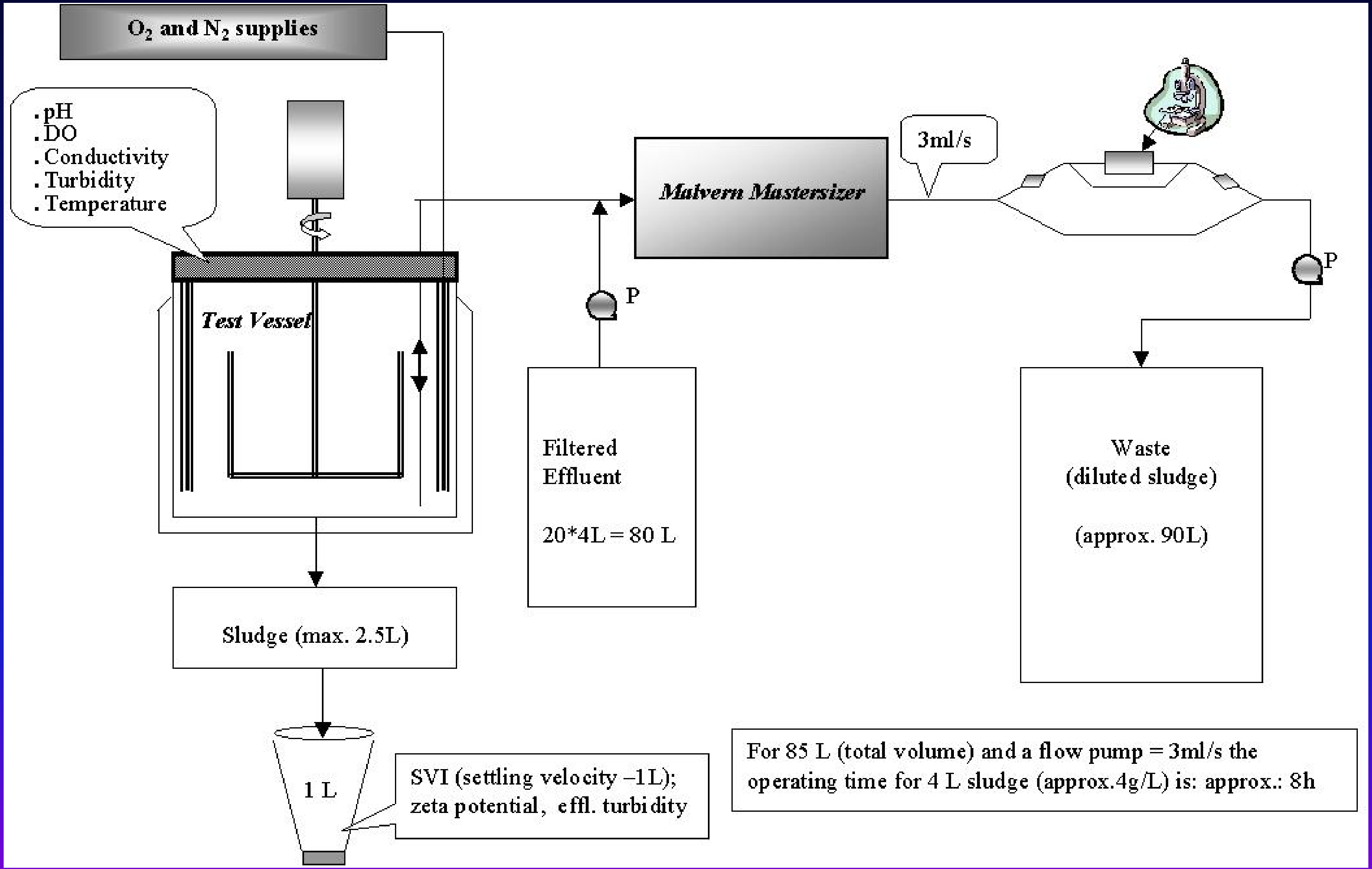
Floc Unit



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Floc Unit

- Features
  - Mobile, T-controlled, bubbleless aeration
  - Measurements:
    - DO, pH, conductivity, torque (on-line)
    - PSD (Malvern, Galai, image analysis) (on-line)
    - SS, SVI, Vs, zeta-potential (after flocculation experiment)
  - Degrees of freedom
    - DO (O_2/N_2-mixture)
    - Torque (viscometer)
    - Temperature
    - SS
    - Ionic strength (ion addition)
  - Statistically based experimental design (full factorial)

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Floc Unit

- Typical experiment
  - standardised starting condition
  - reflocculation in controlled environment
  - apply different environments
  - use orthogonal experimental design
  - flocculation = f(?)
  - implement in PBM

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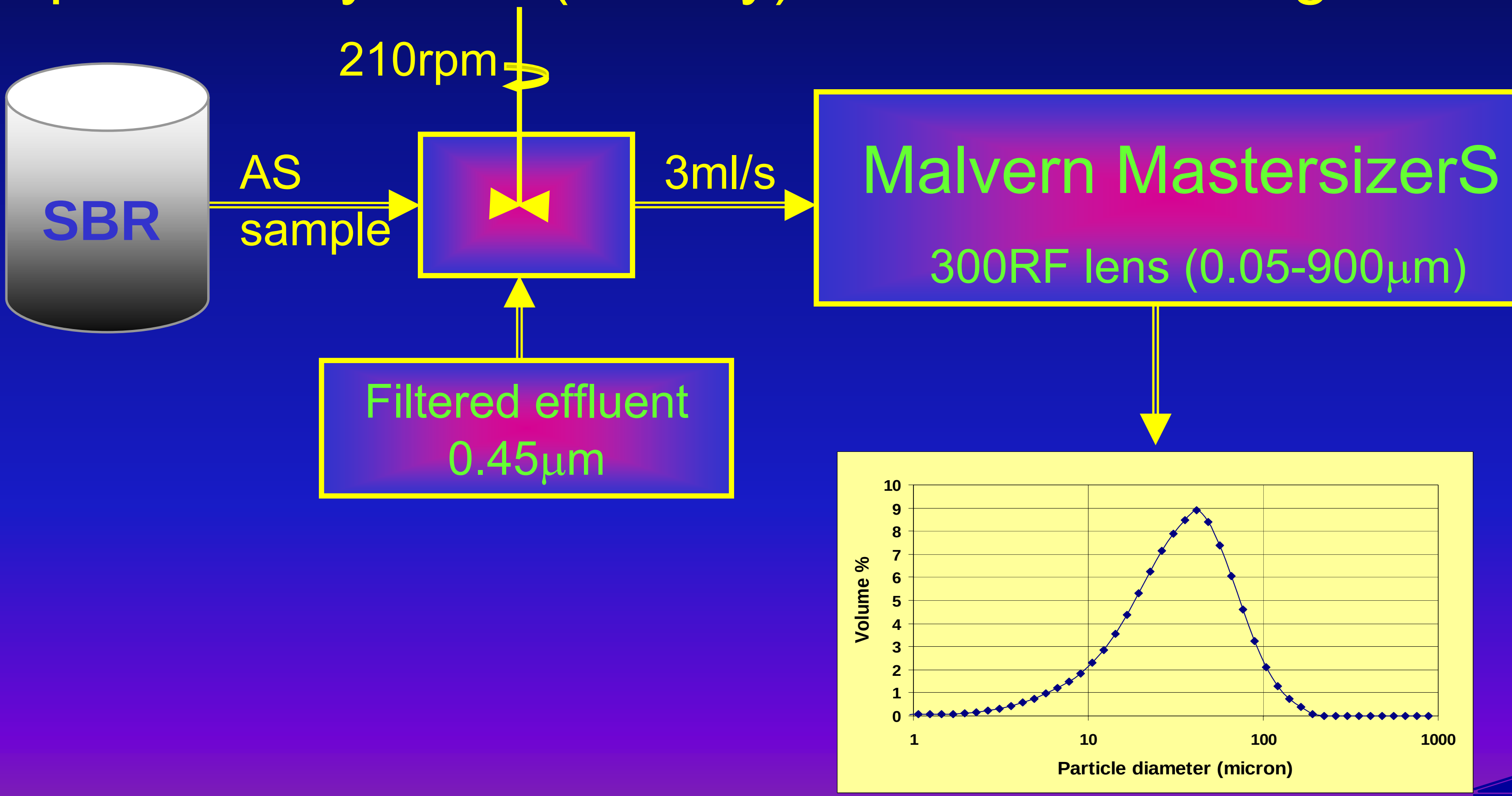
Flocculation knowledge

- On-line determination of PSD
- preliminary tests (weekly) – SBR Monitoring



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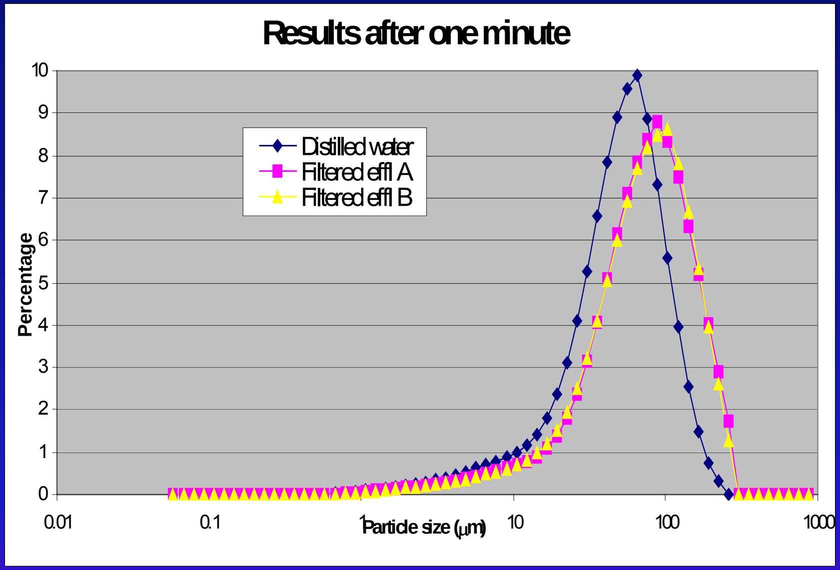
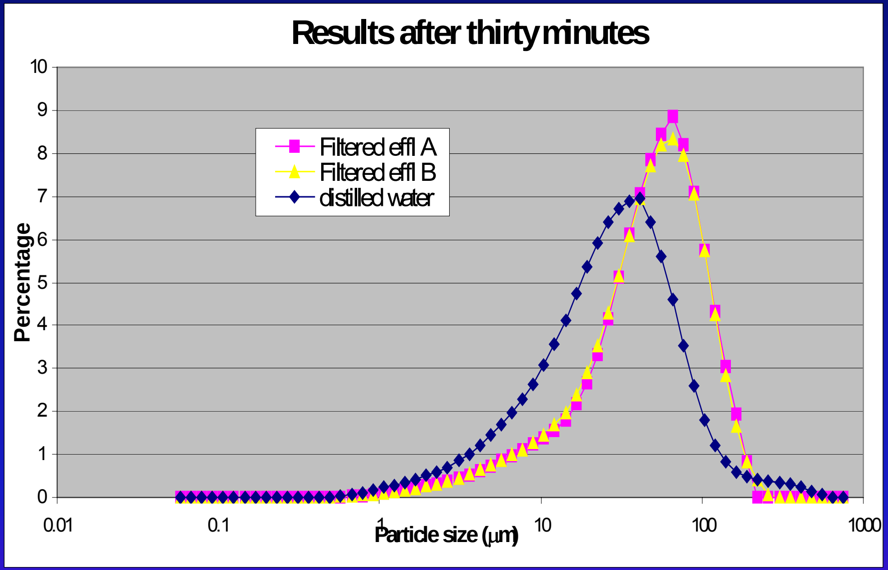
Malvern PSD analysis

- Dilution Influences
  - Distilled water
  - Filter effluent (0,45μm and 0.50 μm)





Diluting the sludge with distilled water caused an increase in the negative surface charge density (Mikkelsen et al. 1996)

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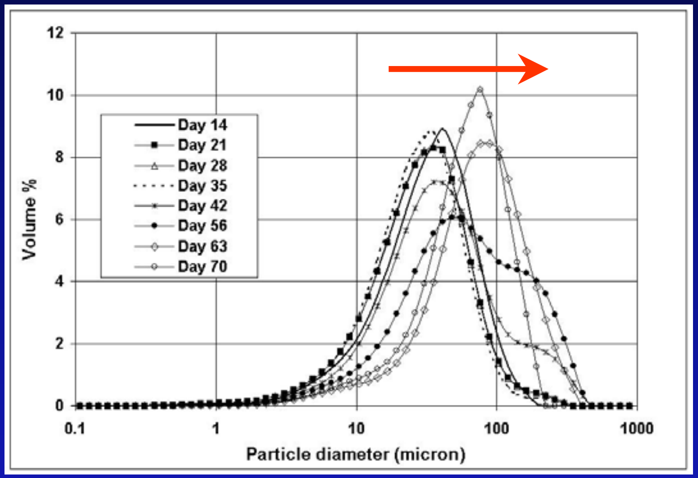
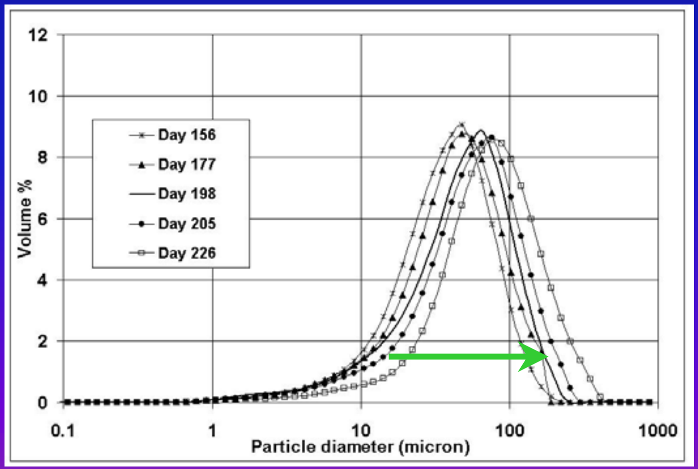
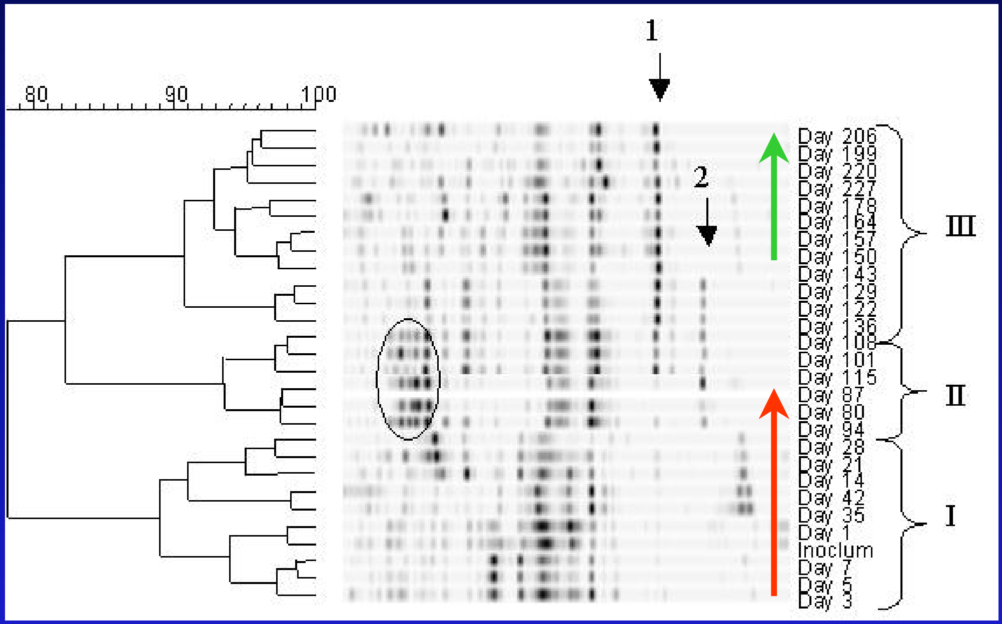
Malvern PSD analysis

- Correlation with DGGE results







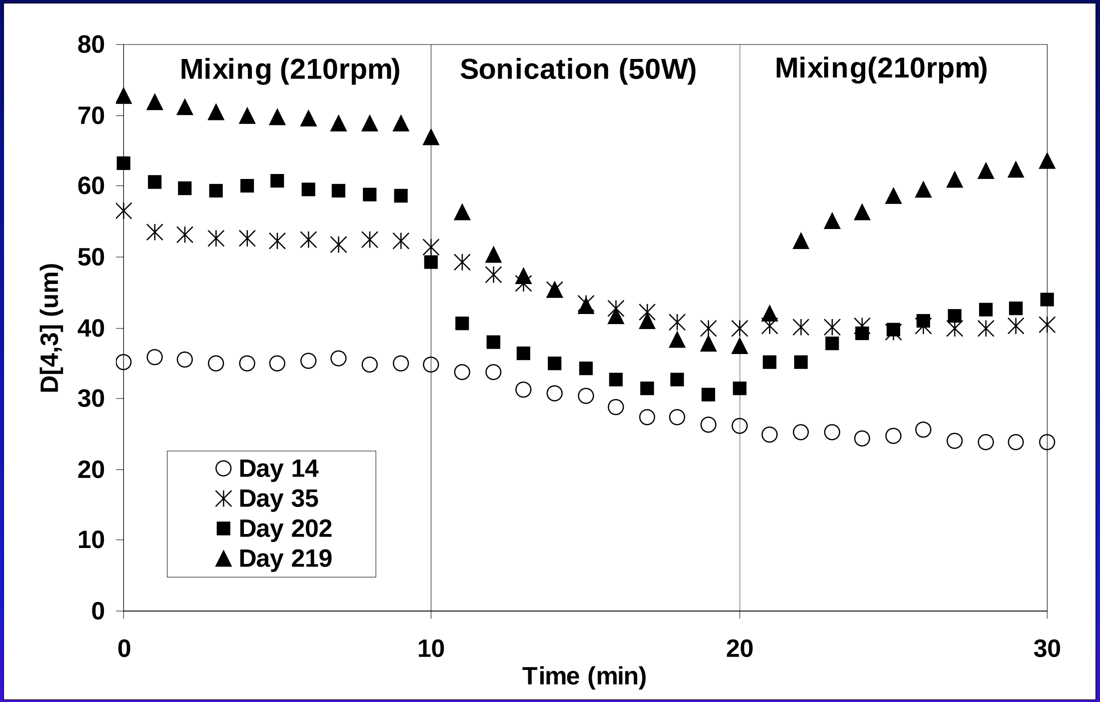
I. Floc forming bacteria

II. Floc forming and filamentous bacteria

III. Filamentous bacteria

Malvern PSD analysis

- Evolution of D[4,3]



$$D[4,3] = \frac{\sum_{i=1}^{n} \Delta F_N(x)_i x_i^4}{\sum_{i=1}^{n} \Delta F_N(x)_i x_i^3}$$

- Non filamentous flocs (days 14 and 35)
- Filamentous flocs (days 202 and 219)

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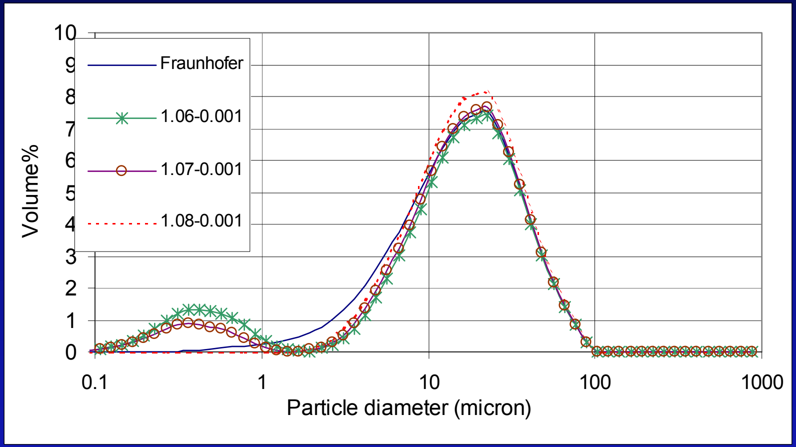
Malvern PSD analysis

- Important remarks
  - drawbacks of Malvern
    - assumption of sphericity
    - dilution is needed
    - Fraunhofer vs Mie theory (refractive indices unknown)



  - combination with on-line image analysis
    - check for differences between PSDs
    - you see what is present
    - on-line image analysis is also possible

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Image analysis (LabView)

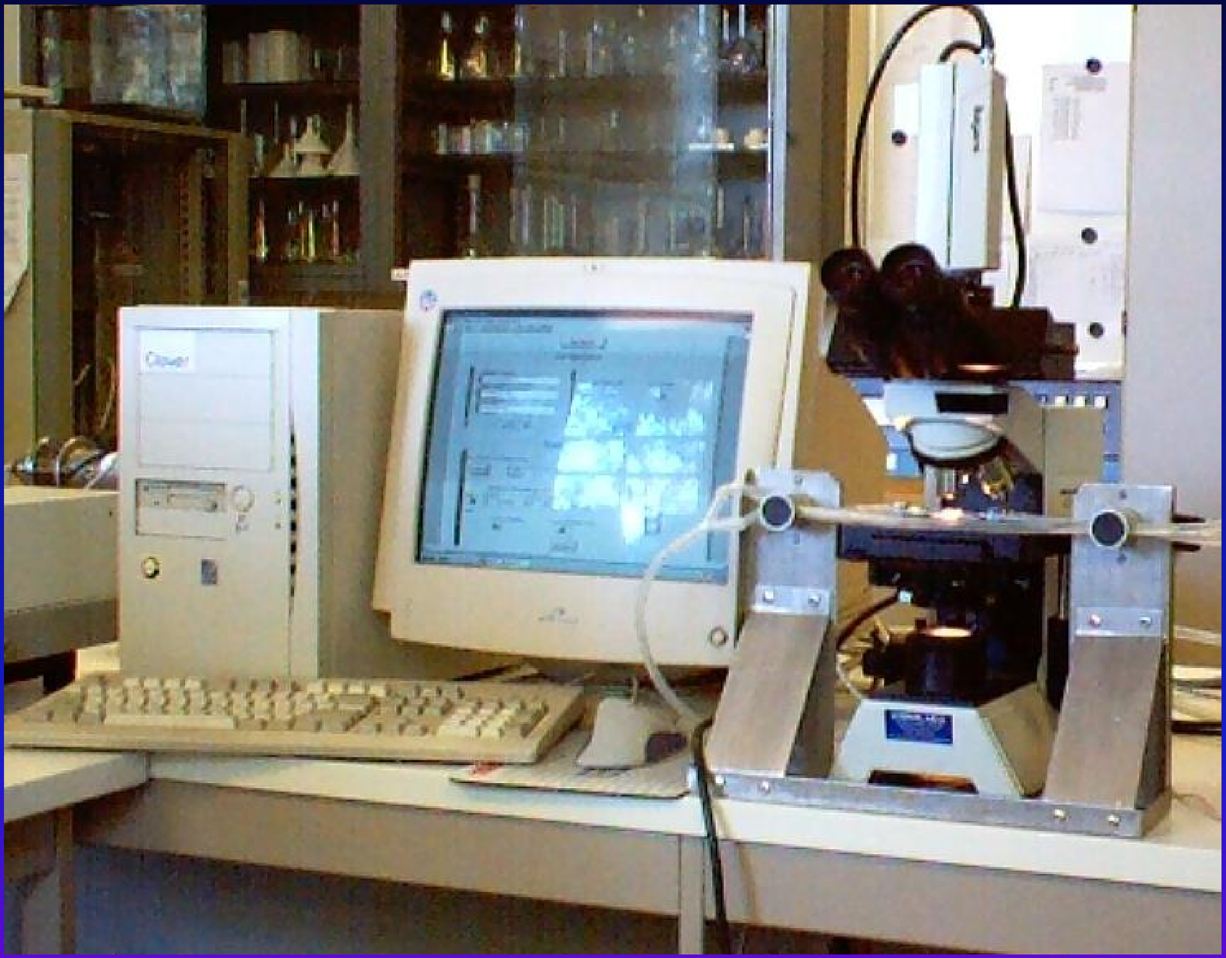
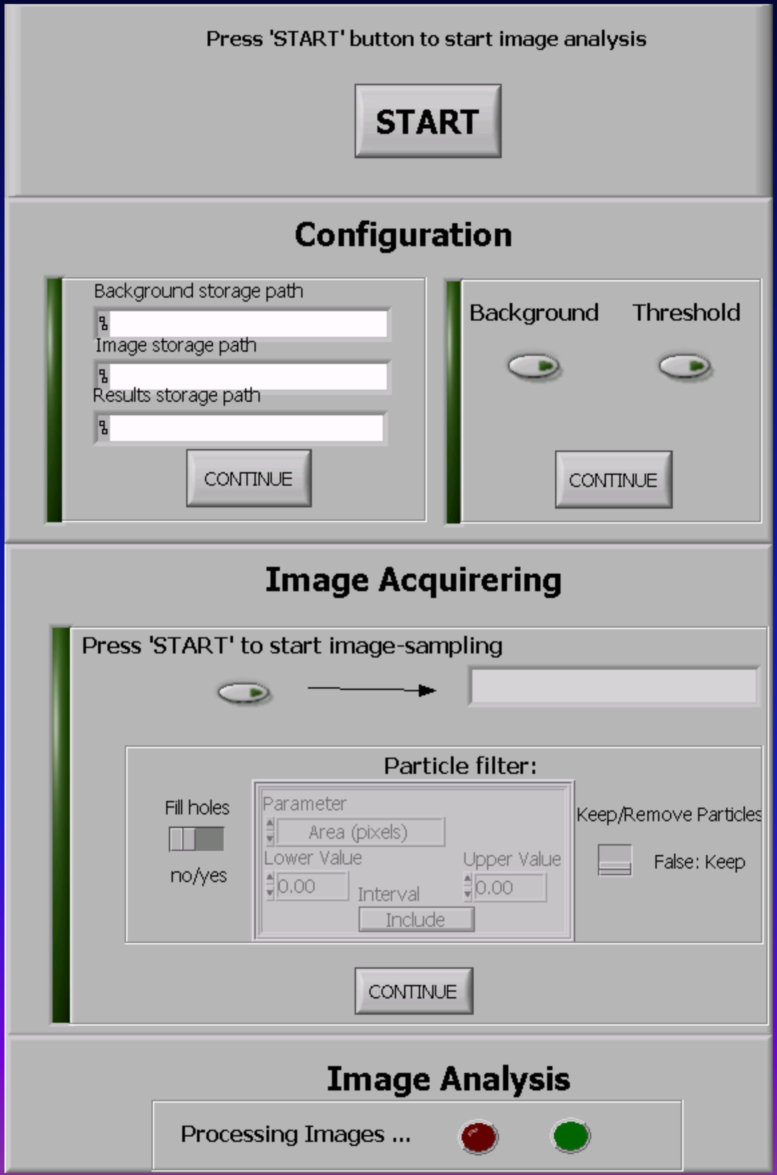
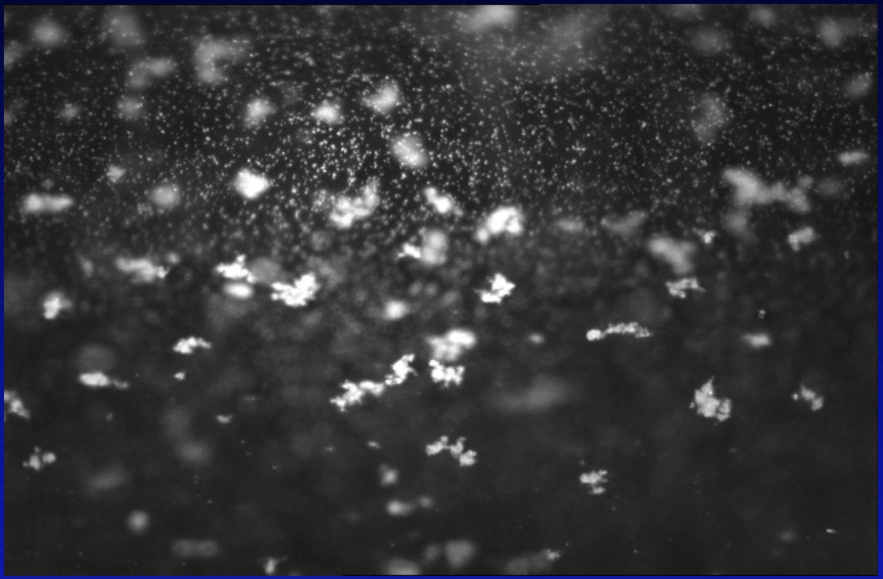
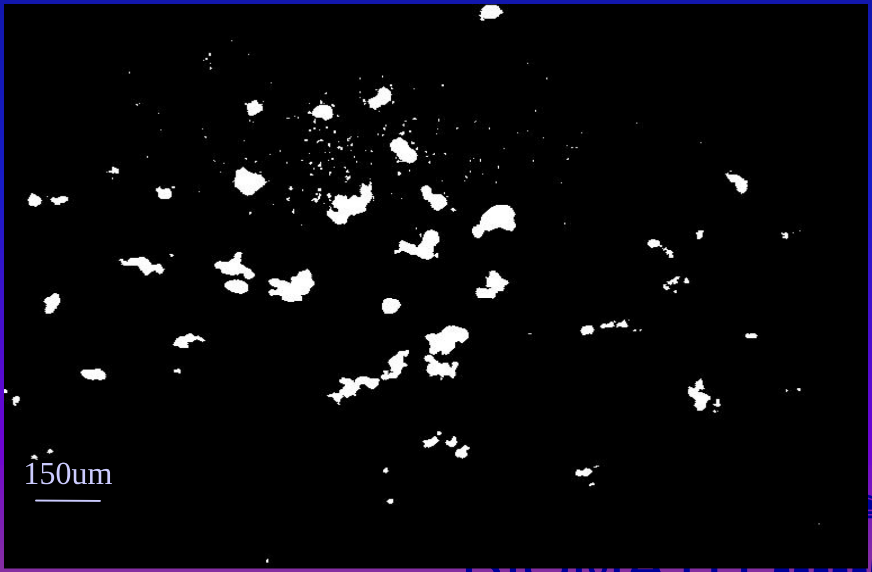


Image analysis (LabView)







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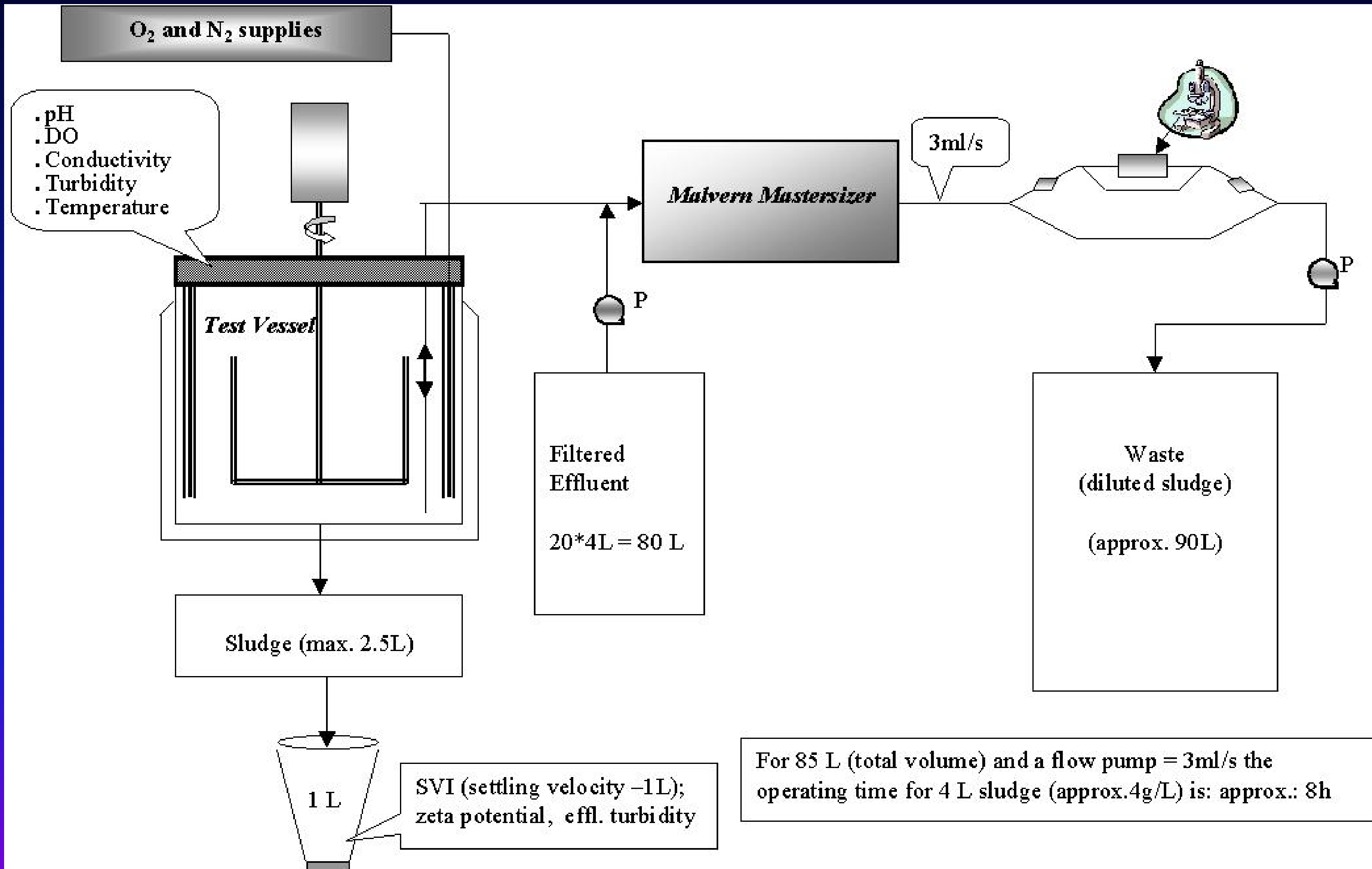
Floc Unit



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- PSD
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- …..

Off-line:
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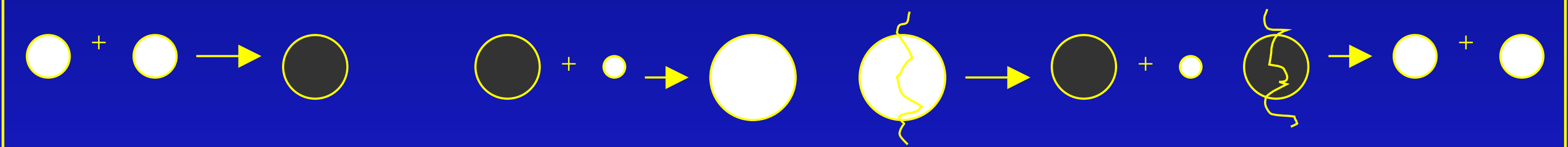
Population Balance Modelling

Hounslow (1988), Biggs (2000)

$$\frac{dN_i}{dt} = aggregation - breakage$$

floc of size, *i*

Aggregation Birth | Aggregation Death | Breakage Birth | Breakage Death



Aggregation Birth: Birth of floc of size, *i* by collision with smaller flocs

$$\frac{dN_i}{dt} = \sum_{j=1}^{i-2} 2^{j-i+1}\alpha\beta_{i-1,j}N_{i-1}N_j + \frac{1}{2}\alpha\beta_{i-1,i-1}N_{i-1}^2$$

Aggregation Death: Death of floc of size, *i* by collision with any other flocs

$$-N_i\sum_{j=1}^{i-1} 2^{j-1}\alpha\beta_{i,j}N_j - N_i\sum_{j=i}^{imax}\alpha\beta_{i,j}N_j$$

Breakage Birth: Birth of floc of size, *i* by breakage of larger flocs

$$+\sum_{j=i}^{imax}\Gamma_{i,j}S_jN_j$$

Breakage Death: Death of floc of size, *i* by breakage of floc of size, *i*

$$-S_iN_i$$

PBM: Model structure - Aggregation

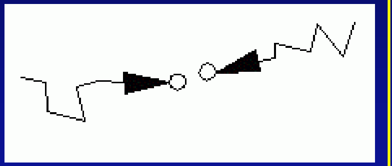
Aggregation kernels (summary)

Collision frequency, β(i,j)

- *Brownian motion*

  $\beta(i,j) = f(T, G, A_H, d(i), d(j), \eta)$

  Smoluchowski (1917)



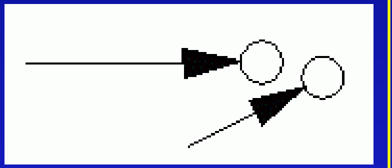
- Shear flocculation

  $\beta(i,j) = f(G, d(i), d(j))$

  Camp & Stein (1943)

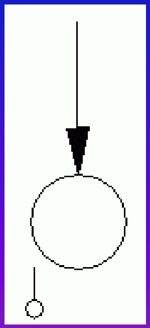
  $\beta(i,j) = f(G, d(i), d(j), D_f)$

  Lee *et al.* (1996)



- Differential sedimentation

  Lee *et al.* (1996)



Collision efficiency, α(i,j)

- $\alpha(i,j)$ = constant
- $\alpha(i,j) = f(\eta, G, A_H, d(i), d(j))$

  Adler (1981)

- $\alpha(i,j) = f(\eta, G, A_H, d(i), d(j), e, \xi)$

  Kusters (1997)

- Ducoste (2002)

G – shear rate | e - porosity

η – viscosity | ξ - permeability

A_H – Hamaker | T - temperature

d – particle diameter

D_f – fractal dimension

PBM: Model structure - Breakage

Breakage kernels (summary)

Breakage frequency, S(i)

- *S(i) = f(d(i))*

  Spicer & Pratsinis (1996)

- *S(i) = f(d(i),* ε,k, *d(i)* ... *)*

  Kusters (1991)

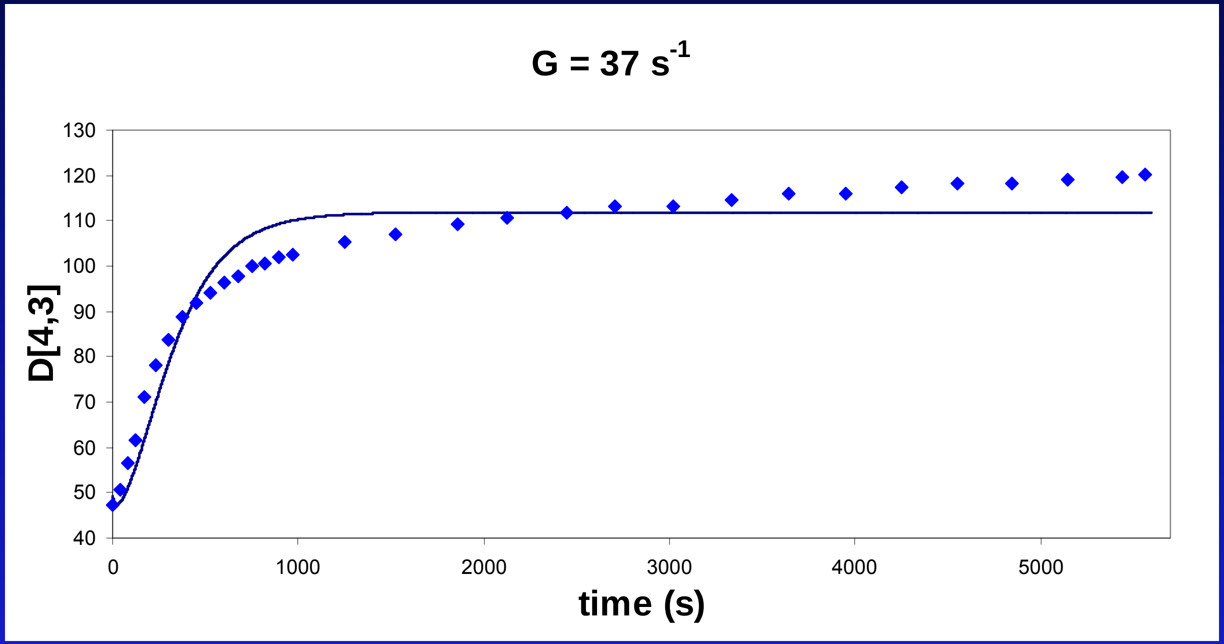
Fragment distribution function, Γ(i,j)

Binary breakage

Different combinations of aggregation and breakage kernels are implemented, simulated and compared to experimental results

PBM: Simulation study

- Model as used by Biggs (2000)
- model fitted on D[4,3]



- too fast / lower steady-state mass mean
- model lacks flexibility

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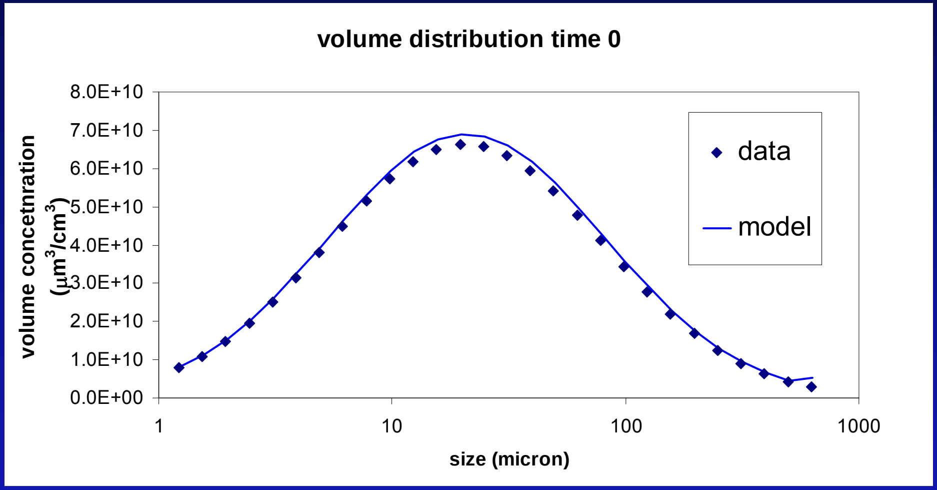
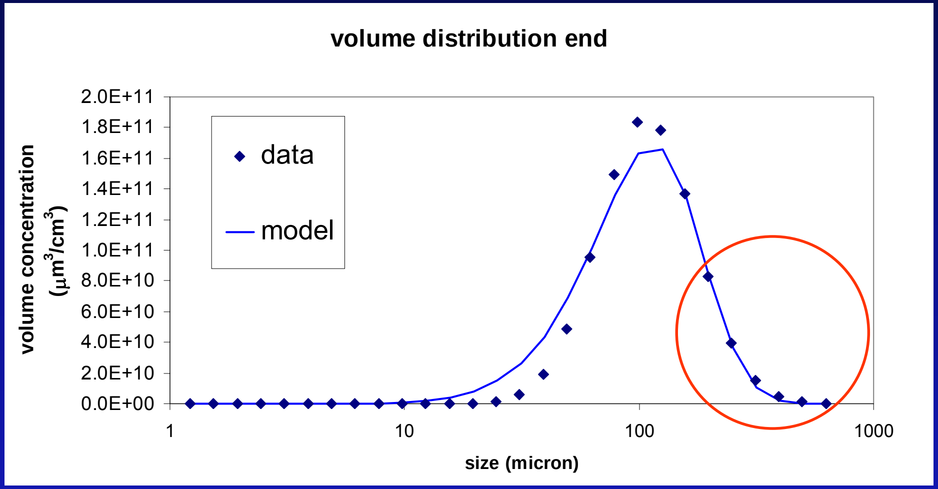
PBM: Simulation study

- inaccurate estimates of PSDs



Volume distribution at time zero



Number distribution at end of experiment

- D[4,3] volume based ➡ fit on PSDs

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2D-clarifier model

- **Aim**
  - Modeling of sludge transport in clarifier, including PBM
  - Computational Fluid Dynamics in Fluent software
  - 2-dimensional
  - Validation of CFD-model by
    - tracer test
    - solids concentration
    - particle size distributions
    - velocities

2D-clarifier model (cont'd)

- **Model equations for CFD:**

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i$$

$$\tau_{ij} = (\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}(\mu + \mu_t)\frac{\partial u_l}{\partial x_l}\delta_{ij}$$

Sludge transport equation:

$$\frac{\partial}{\partial t}(\rho \phi) + \frac{\partial}{\partial x_i}\left[\rho \phi (u_i + v_i) - \Gamma \frac{\partial \phi}{\partial x_i}\right] = 0$$

Density:

$$\rho = \frac{\rho_w}{1 - \phi\left(1 - \frac{\rho_w}{\rho_s}\right)}$$

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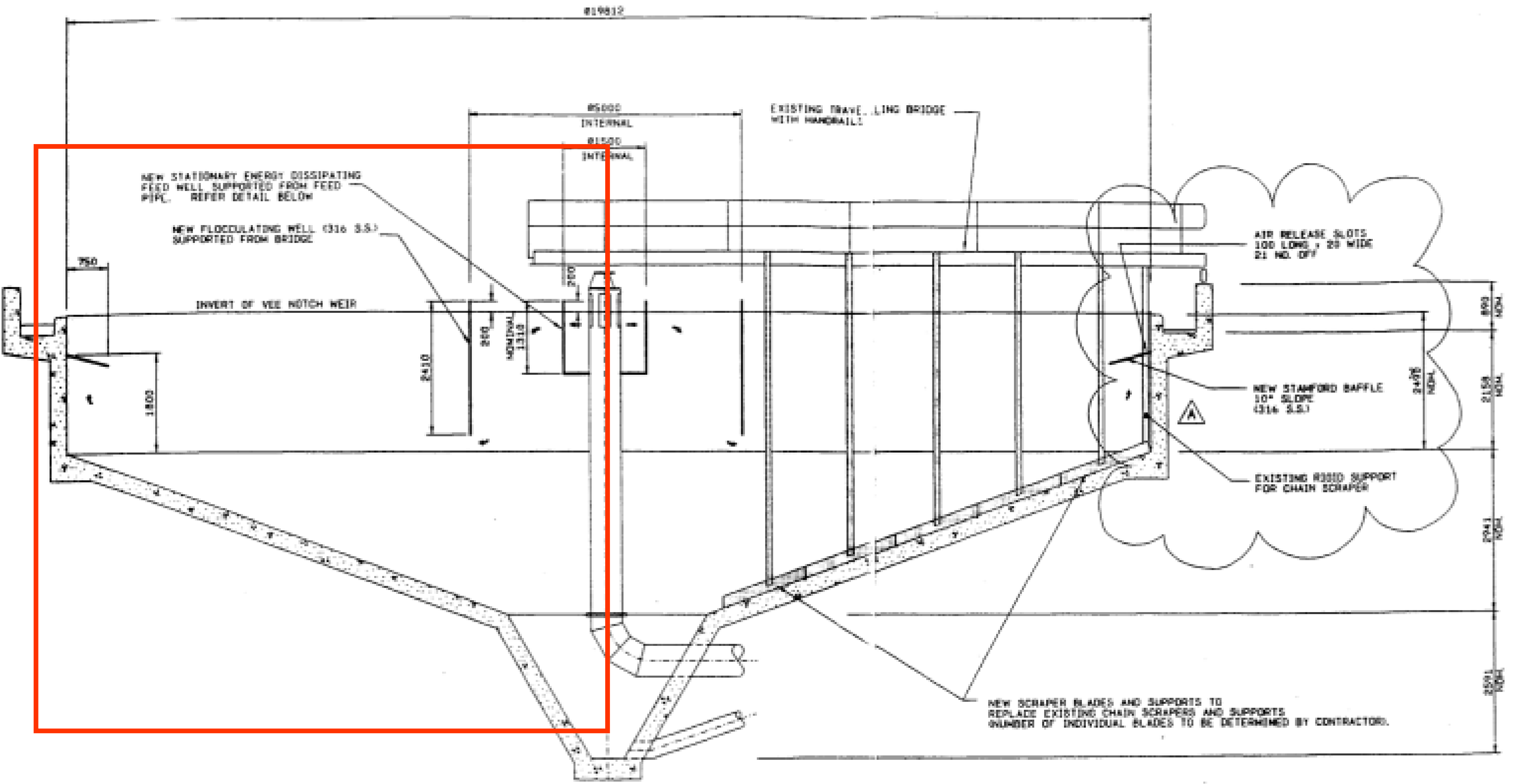
2D-clarifier model (cont'd)

- **Oxley Creek settling tank**



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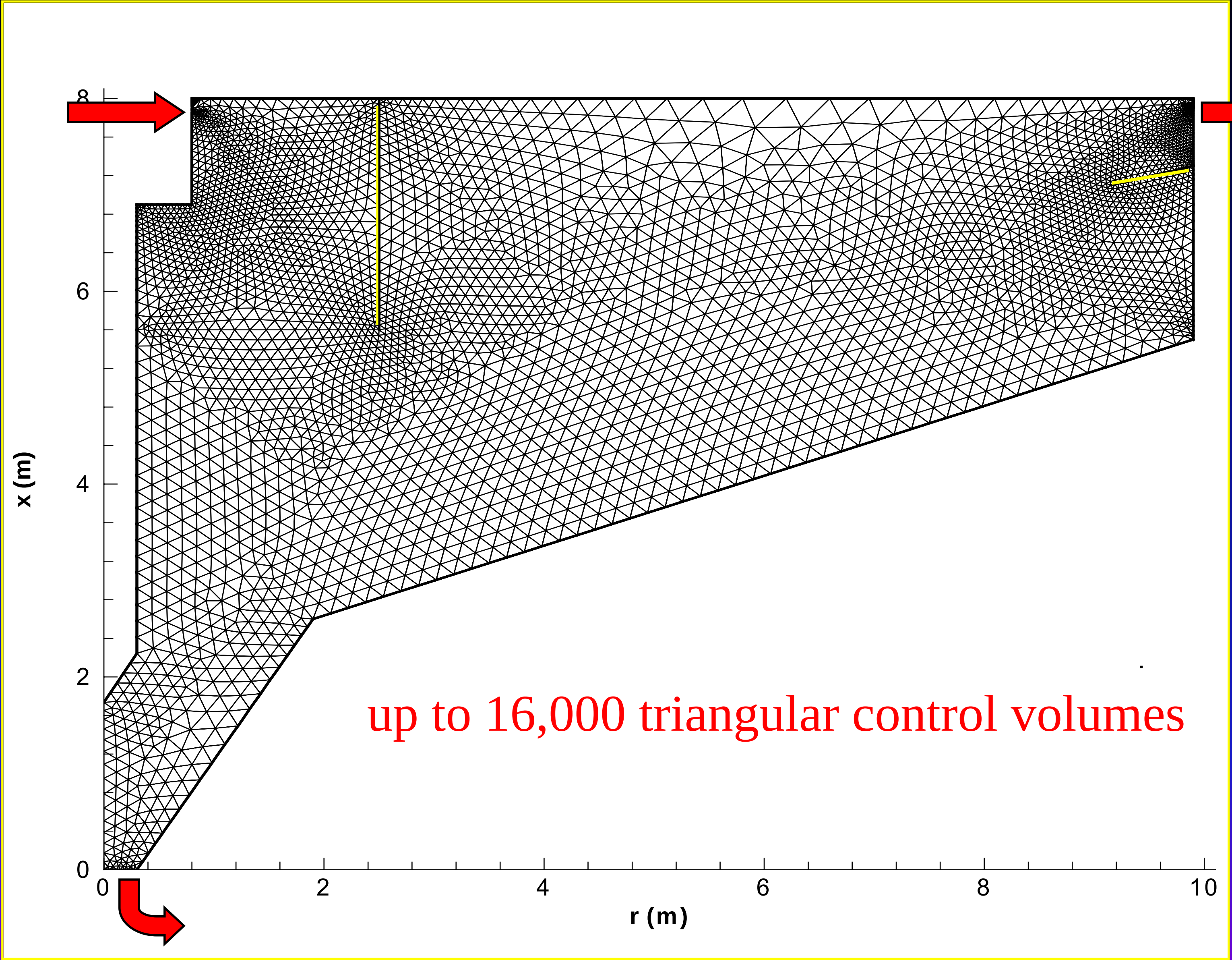

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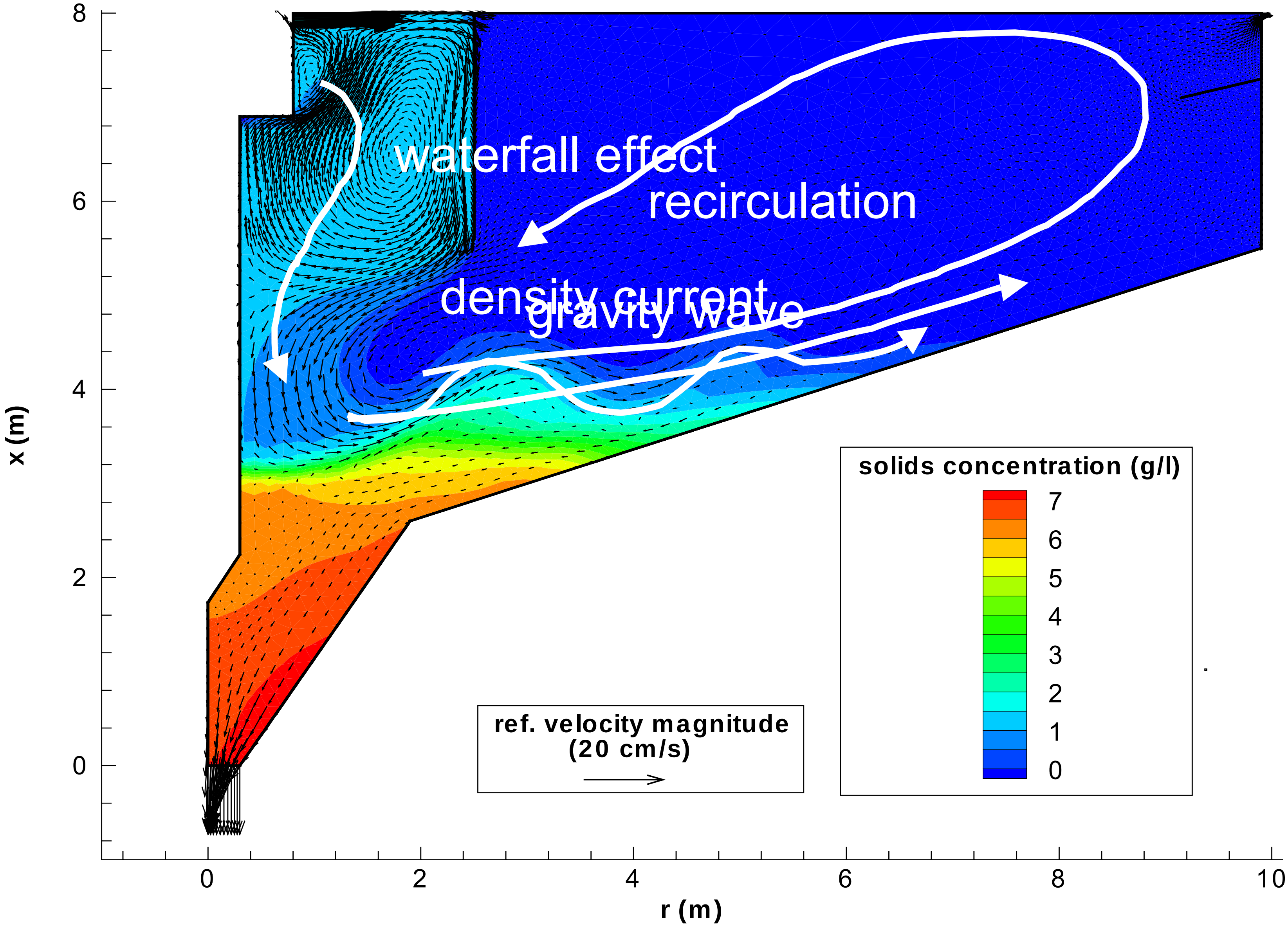
waterfall effect
recirculation
density current
gravity wave
x (m)
r (m)
8
6
4
2
0
0
2
4
6
8
10
ref. velocity magnitude
(20 cm/s)
solids concentration (g/l)
7
6
5
4
3
2
1
0

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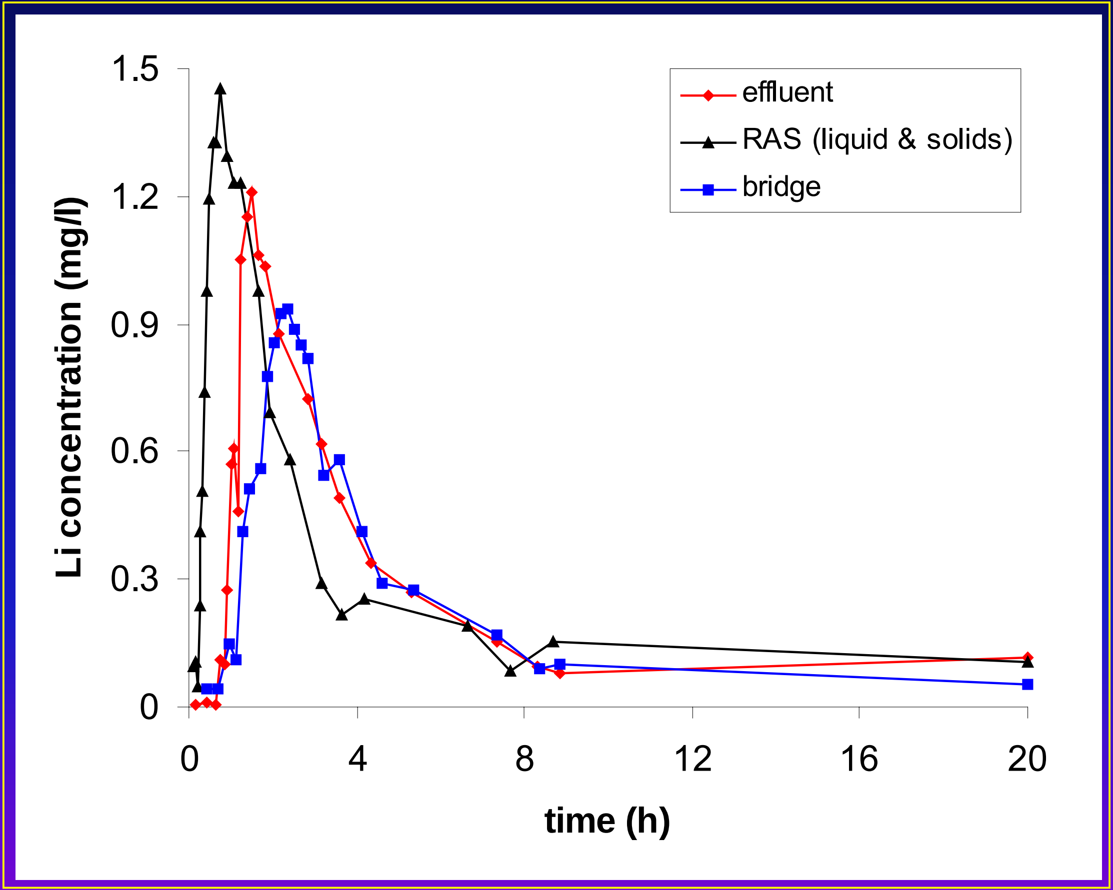
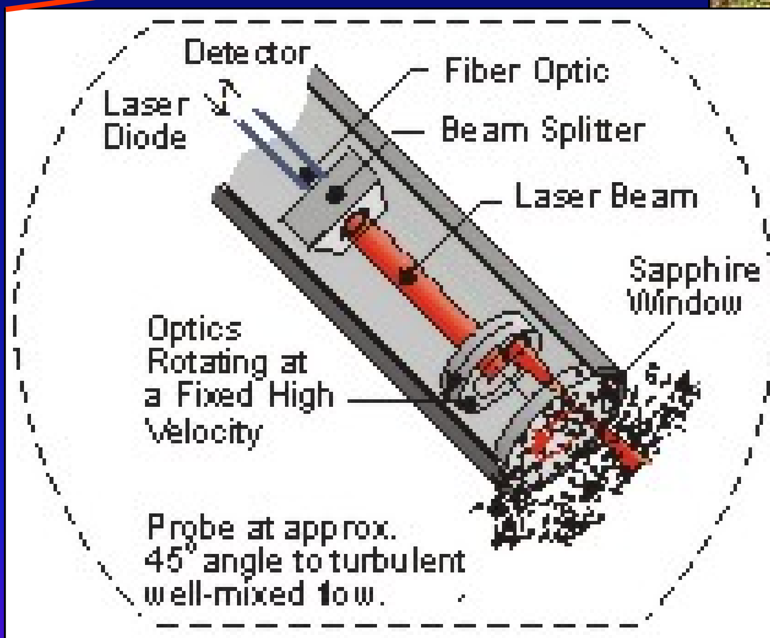
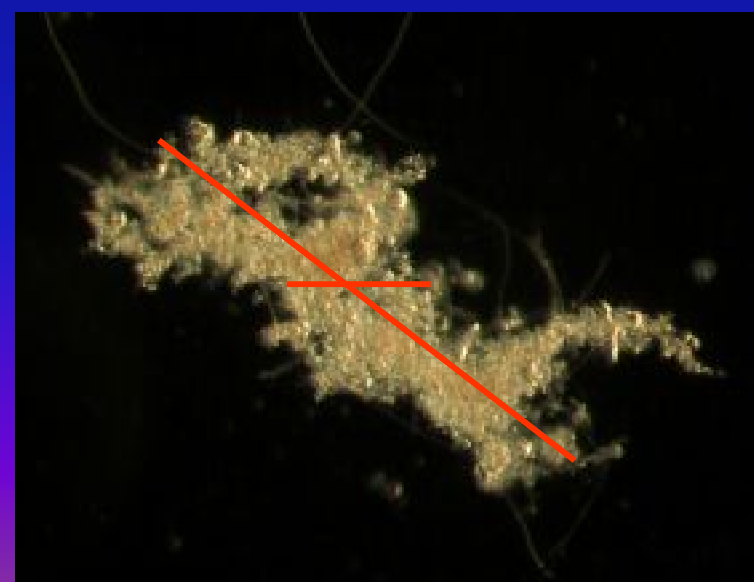
2D-clarifier model (cont'd)

- **Results of tracer test (LiCl)**

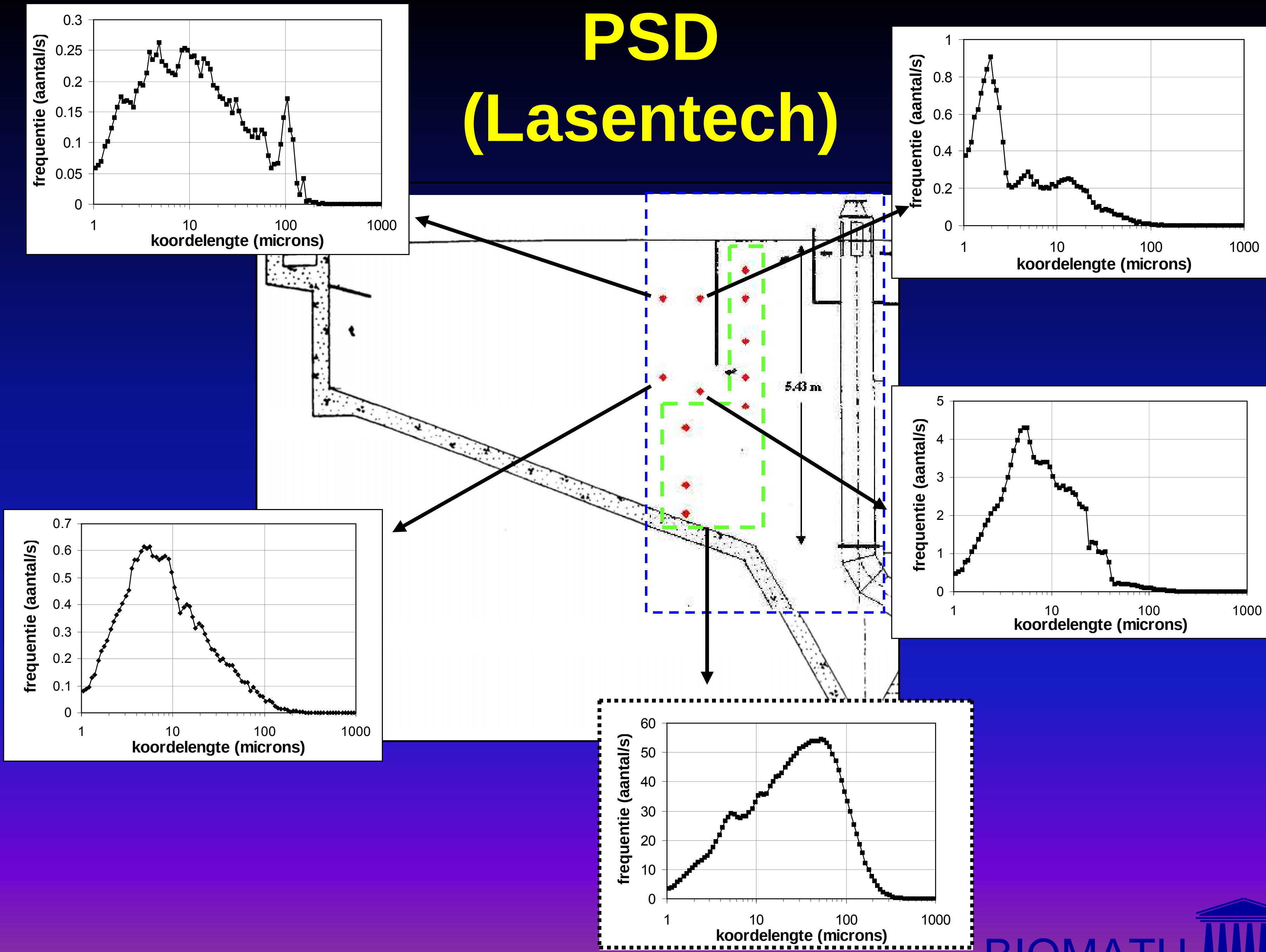


In situ PSD (Lasentech)





PSD (Lasentech)



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1D-clarifier model with dispersion

- Continuity equation:

$$\frac{\partial C(z,t)}{\partial t} = -\frac{\partial (F(C(z,t),z,t)}{\partial z} + \frac{\partial}{\partial z}\left(D(z,t) * \frac{\partial C(z,t)}{\partial z} \right) + s(z,t)$$

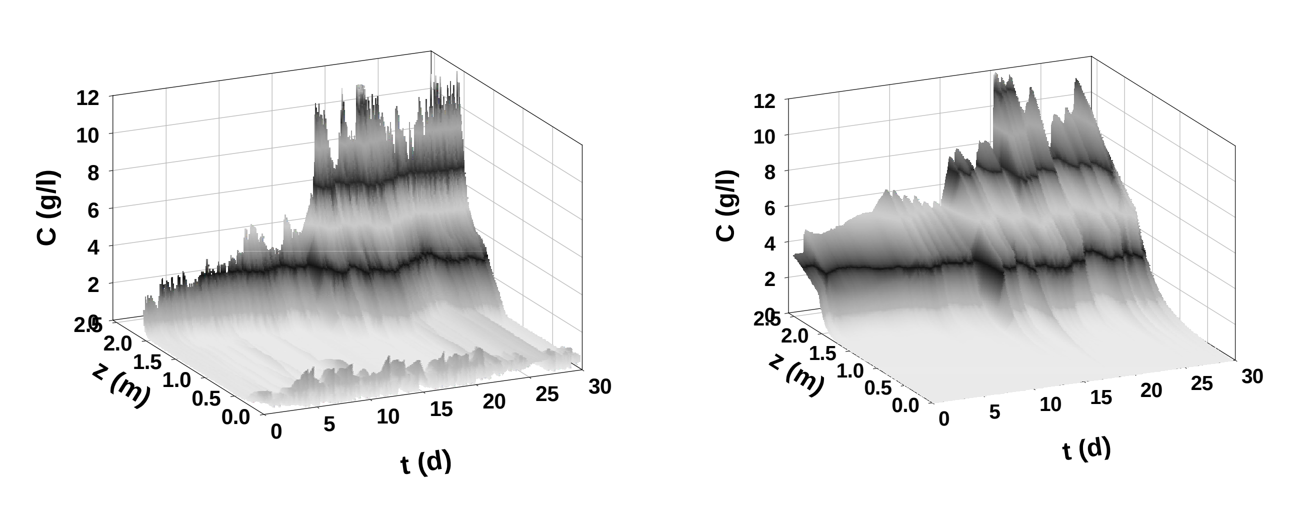
- Dispersion for clarification and thickening zone:

$$D_1(t) = D_{11} * e^{\alpha * \frac{Q_e(t)}{Q_f(t)}} \qquad D_2(t) = D_{22} * e^{\beta * \frac{Q_u(t)}{Q_f(t)}}$$

- Variable location of feed layer to consider density currents
- Numerical integration
  – differencing of spatial derivatives of PDE (100 layers)
  – LSODA for numerical integration of (stiff) ODE system

1D-clarifier model (3)

- Measured (left) and predicted (right) sludge profile vs time



- Dynamics are described well

- Discrepancy at concentrations higher than 6 g/l, but good results for $C_{recycle}$

BIOMATH

SBR (80L)
sludge breeding

-STABILITY-

Monitoring:

On-line:
- DO concentration
- pH

Off-line:

Effluent:
- COD
- N_{total}, NO_2-N, NO_3-N, NH_3
- PO_4-P

Sludge
- MLSS, MLVSS, SVI
- DGGE (microbial stability)

Influent
- 7 days stability

Floc Unit (5L)
flocculation experiments

-DYNAMICS-

Monitoring:

On-line:
- DO concentration
- pH
- Conductivity
- Shear stress
- PSD
- Image analysis
- …..

Off-line:
- Settling velocity
- SVI

Flocculation Knowledge

Population Balance Modelling (PBM)

2D-Clarifier Modelling

COMPUTATIONAL FLUID DYNAMICS (CFD)

Prediction of velocity, AS-conc. pattern

Virtual Optimal Experimental Design
(Virtual OED)

1D-Clarifier Modelling

BIOMATH

Virtual Optimal Experimental Design

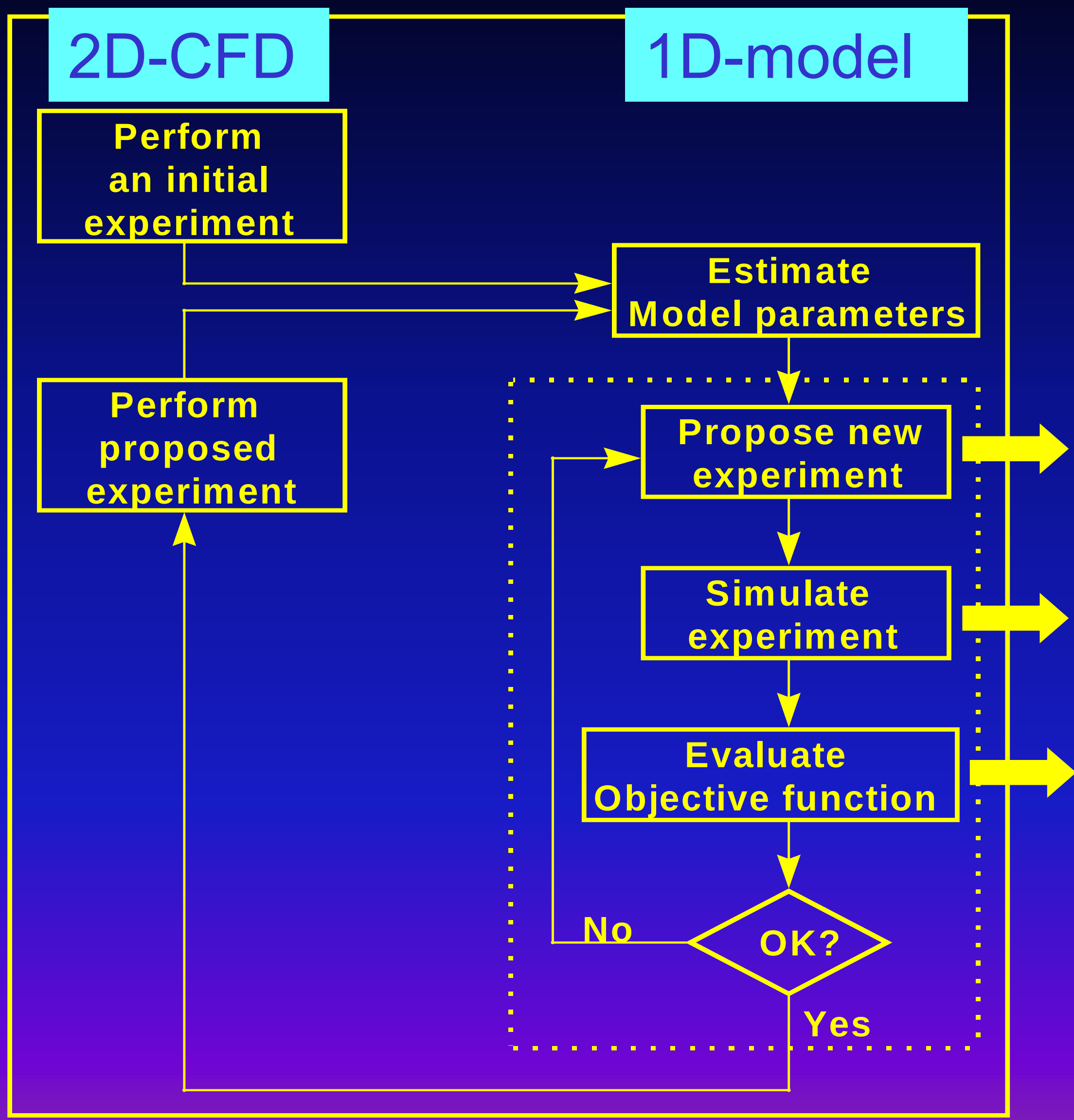
- Bridge between 1D and 2D clarifier models

  =Knowledge transfer mechanism

- Propose simulation experiments (measure where you like !) to be performed with 2D CFD clarifier model for optimal calibration (low errors on parameters) of the 1D clarifier model

- Tool = WEST
- Implementations performed in WEST:
  - Sensitivity analysis
  - Fisher Information Matrix evaluation (information content)
  - Optimal Experimental Design criteria

Experimental design methodology



Experimental degrees of freedom

(Sensitivity analysis) FIM calculation

Evaluate FIM criterion

SBR (80L)
sludge breeding

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Flocculation Knowledge ↔ **Population Balance Modelling (PBM)**

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