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# DYNAMIC SIMULATION OF SLUDGE BLANKET MOVEMENTS IN A FULL-SCALE RECTANGULAR SEDIMENTATION BASIN

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## ABSTRACT

Bromma sewage treatment plant in Stockholm is the second largest plant in Stockholm and will in the near future have requirements for nitrogen removal. This means that a higher sludge age must be used in the aeration basin. This may be accomplished by an increase of the sludge concentration up to values until the limiting solids flux is exceeded. Measurement of the sludge blanket level is a possibility for better control of the sedimentation basin. Different measurements were performed to evaluate the main factors influencing the level.

Dynamic simulation studies were performed at Bromma sewage treatment plant in Stockholm of the sludge blanket level and the return sludge concentration in a full-scale sedimentation basin. The simulations were performed with the help of a Danish simulation package, EFOR (1992), in which both reactions in the aeration basin (mainly based on the IAWPRC model) and separation processes in the sedimentation basin (both clarification and thickening) can be studied. The thickening model is based on the solids flux theory and the Vesilind formula (1979). Different methods were compared for determination and use of characteristic parameters in the Vesilind formula. Copyright © 1996 IAWQ. Published by Elsevier Science Ltd.

## KEYWORDS

Activated sludge; EFOR; sedimentation; simulation; sludge blanket; solids flux; thickening; wastewater.

## NOMENCLATURE

$G$ = Solids flux (kg /m$^2$ h)
$G_{bsed}$ = Solids flux in the sedimentation basin due to sedimentation (kg /m$^2$ h)
$G_{in}$ = Incoming solids flux to the sedimentation basin (kg /m$^2$ h)
$G_l$ = Limiting solids flux (kg /m$^2$ h)
$G_{max}$ = Maximum flux according to solids flux theory (kg /m$^2$ h)
$G_r$ = Solids flux in the return sludge (kg /m$^2$ h)
$G_{sed}$ = Solids flux in the sedimentation basin (kg /m$^2$ h)
$n$ = Settling parameter in the Vesilind model (m$^3$/kg)
$q_{in}$ = Influent flow/sedimentation basin area (m/h)

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$q_r$ = Return sludge flow/sedimentation basin area (m/h)
$SSV_{30}$ = Stirred specific volume (ml/l)
$SSVI_{3.5}$ = Stirred specific volume index at MLSS = 3.5 g/l (ml/g)
SVI = Sludge volume index (ml/g)
V = Sedimentation velocity (m/h)
$V_0$ = Settling parameter in the Vesilind model (m/h)
X = Activated sludge concentration ($kg/m^3$)
$X_l$ = Limiting activated sludge concentration ($kg/m^3$)
$X_{in}$ = Activated sludge concentration in the inlet to the sedimentation basin ($kg/m^3$)
$X_r$ = Activated sludge concentration in the return sludge ($kg/m^3$)

## INTRODUCTION

Bromma sewage treatment plant is the second largest plant in Stockholm and is at present designed for a sewage flow of 160,000 $m^3/d$ and a $BOD_7$ load of 30,000 kg/d. The treatment plant has a pre-precipitation stage followed by the activated sludge process and deep-bed filters for polishing. In the near future the treatment plant will have requirements for nitrogen removal. This means that the plant must be operated with a high sludge age. A possibility is to increase the sludge concentration in the aeration basin. However, the sludge sedimentation properties are often poor, with sludge volume indices above 200 ml/g, especially during the late winter months and early spring. During such periods a critical situation may appear with a rising sludge level followed by sludge escape as soon as the hydraulic load increases about 30% above average daily values. An increased knowledge of the behaviour of the sedimentation basin is therefore essential. The treatment plant has 12 secondary sedimentation basins with a total area of 5630 $m^2$.

## THEORY

An activated sludge process with an aeration basin and a sedimentation basin is schematically shown in Figure 1. Under steady-state conditions and with no sludge escape the incoming flux ($G_{in}$) to the sedimentation basin, the solids flux ($G_{sed}$) in the sedimentation basin and the solids flux ($G_r$) in the return sludge are equal. The solid fluxes may be written:

$$G_{in} = Xin(q_{in} + q_r) \tag{1}$$

$$G_{sed} = X(V + q_r) \tag{2}$$

$$G_r = X_r q_r \tag{3}$$

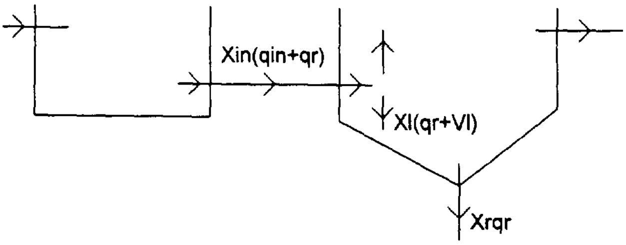

Figure 1. Solids flux in a secondary sedimentation basin.

The limiting solids flux ($G_l$) is related to the limiting solids concentration ($X_l$) below the inlet point in the sedimentation basin. If the incoming flux exceeds the limiting value, the sludge blanket grows until sludge escape occurs (Balslev *et al.*, 1994; Dick, 1970; Ekama *et al.*, 1984; Keinath, 1985; Ong, 1992).

The solids flux due to sedimentation only in the sedimentation basin, $G_{bsed}$ may be written:

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$$G_{bsed} = VX \tag{4}$$

The formula by Vesilind (1979) is often used for expressing the sedimentation velocity as a function of the sludge concentration:

$$V = V_0\exp(-\,nX) \tag{5}$$

Formula 5 is inserted in formula 4:

$$G_{bsed} = V_0X\exp(-\,nX) \tag{6}$$

Formula 6 may be rewritten as:

$$\frac{nG_{bsed}}{V_0} = nX\exp(-\,nX) \tag{7}$$

Formula 7 is shown in Figure 2 in a diagram of $nG/V_0$ as a function of nX and may be regarded as a dimensionless solid flux plot (cf Baskin and Suidan, 1985; Balslev *et al.*, 1994).

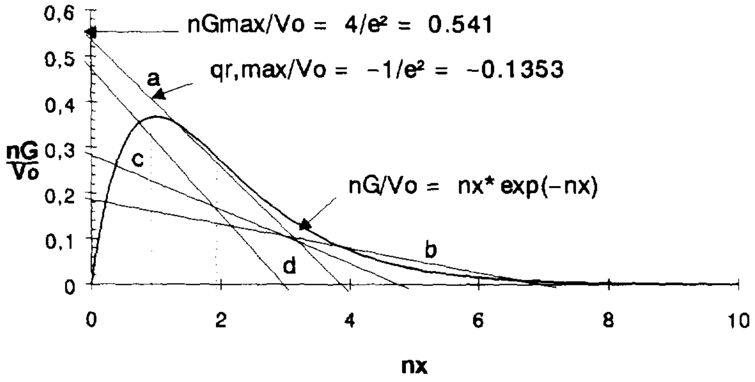

Figure 2. Solids flux curve in a dimensionless form.

Several studies have been done to combine the solids flux theory with the Vesilind formula (Vesilind, 1979). It may be shown that the solid flux theory may be applied if the following conditions are satisfied:

$$nX_r \quad 4 \tag{8}$$

$$q_r \quad V_0/e^2 = 0.1353 \tag{9}$$

If $nX_r = 4$ and $q_r = V_0/e^2$ the maximum solids flux ($G_{max}$) is obtained and can be shown to be:

$$G_{max} = 4V_0/ne^2 = 0.541{*}V_0/n \tag{10}$$

In Figure 2 four operational lines are shown with the following meanings:

| | |
|---|---|
| Line a: | tangent drawn to the inflexion point of the curve showing operational conditions where maximum solids flux is obtained |
| Line b: | operational conditions where the influent solids flux is higher than the limiting flux, i.e. the sludge blanket grows |
| Line c: | operational conditions where the influent solids flux is lower than the limiting flux |
| Line d: | operational conditions outside the limits of the solids flux theory |

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Instead of using solid flux diagrams to estimate limiting solids flux conditions, it is possible to obtain an analytical solution if the Vesilind formula is used. The solution shows on a rather complex relationship. For values of $nX_r$ between 4 and 7 the relationship may approximately be written as (Li, 1995):

$$G_l = \frac{q_r \ln(2.88V_o / q_r)}{0.7484n} \tag{11}$$

Many relationships have been developed to describe the sludge settling parameters $V_0$ and n in the Vesilind formula as a function of different sludge indices (Hultman *et al.*, 1991). Recently published relationships include those of Härtel and Pöpel (1992) and Daigger (1995).

Härtel and Pöpel (1992):

$$V_o = 17.4\exp(-0.0113SVI) + 3.931 \tag{12}$$

$$n = -0.9843\exp(-0.00581SVI) + 1.043 \tag{13}$$

Daigger (1995):

$$V_o = 7.973 \text{ (for } SSVI_{3.5}) \tag{14}$$

$$n = 0.0583 + 0.00405SSVI_{3.5} \tag{15}$$

Formulas 12 and 13 or 14 and 15 may be used to calculate $V_o/n$ as a function of the sludge index or in combination with formula 11 to calculate the limiting solids flux as a function of sludge index and $q_r$.

## MATERIALS AND METHODS

Experimental studies were performed in a full-scale rectangular sedimentation basin, with a depth of 5.6 m and an area of 470 $m^2$ (see Figure 3). The basin was served with four return sludge pumps, each with a capacity of approximately 35-40 l/s. The sludge in the sedimentation basin is pushed to the pumps with the help of four line-pulled scrapers set at a speed of 17 m/h. A sludge concentration meter based on measurements of transmitted light (Cerlic SSM-µP) was installed just before the entrance of the return sludge into the activated sludge basin. The sludge level was measured by a sludge meter measuring the sludge level discontinuously (every six minutes by putting down a sensor to monitor the sludge level (Cerlic SBM-µP).

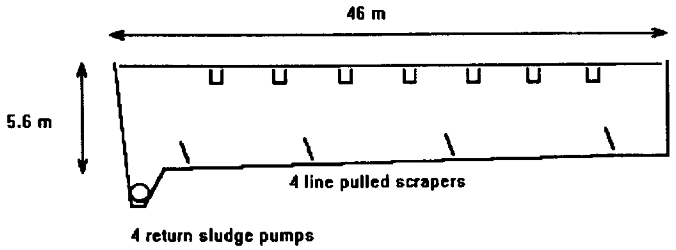

Figure 3. The sedimentation tank.

Because of the construction of the connection between the settling tank and the aeration tank, it has always been very difficult to estimate the flow rate of the return sludge at the Bromma sewage treatment plant. Figure 4 shows how the return sludge, transported by a rectangular drain, enters the aeration tank and the use of ultrasonic devices for measuring of the flow.

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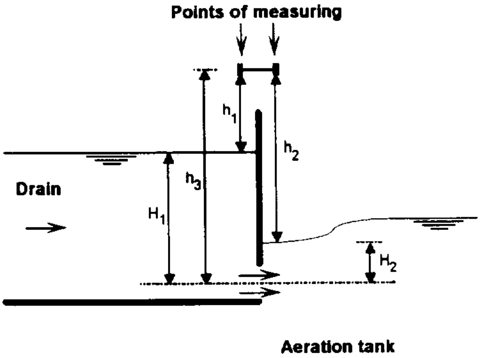

Figure 4. Estimating the flow rate of the return sludge by using small ultrasonic devices and the formula $Q = \mu * A * [2g * ( H1 - H2)]^{1/2}$, where $\mu$ is the coefficient of discharge, A the area of the rectangular discharge gate and g the gravitation.

In the studies of factors affecting the sludge blanket level and movements two different studies were performed. In the first study the average sludge blanket level was studied on twenty different days during the period 1993-05-12 - 1994-04-28 as a function of different parameters. The movements of the sludge blanket level were studied during two days (1994-03-07 - 1994-03-08).

## RESULTS

### Sludge properties, operational conditions and sludge blanket levels

Several tests with the Water Research Centre apparatus had shown an excellent agreement between experimental results and the Vesilind formula. An example is shown in Figure 5. Obtained values for $V_0$ and n were 6.58 m/h and 0.64 $m^3/kg$, respectively. Similar tests were performed on other days during the period 1993-05-12 - 1994-04-28 in order to determine $V_0$ and n, respectively, as functions of $SSVI_{3.5}$ (see Figure 6). The obtained results were in general agreement with relationships by Härtel and Pöpel (if SVI was substituted by $SSVI_{3.5}$ in formulae 12 and 13) and by Daigger (formulae 14 and 15).

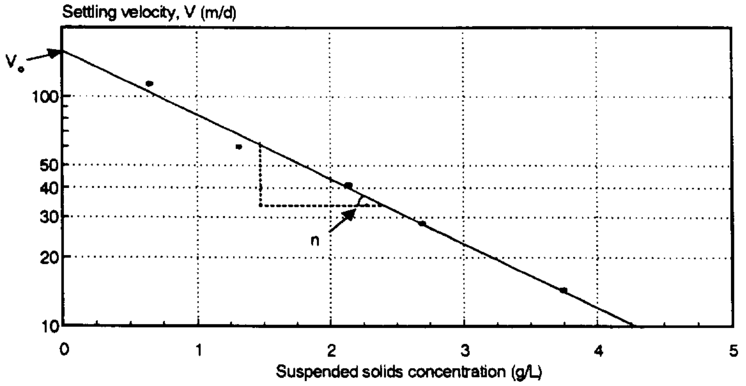

Figure 5. Settling velocity as a function of the suspended solids concentration.

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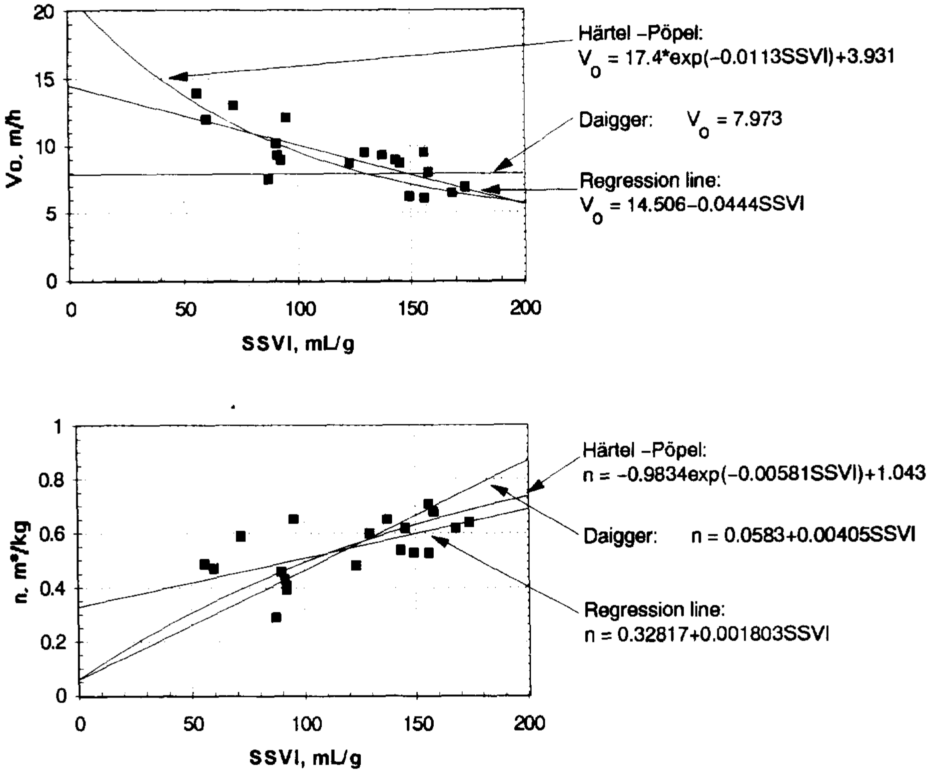

Figure 6. Settling parameters $V_0$ and n as a function of $SSVI_{3.5}$.

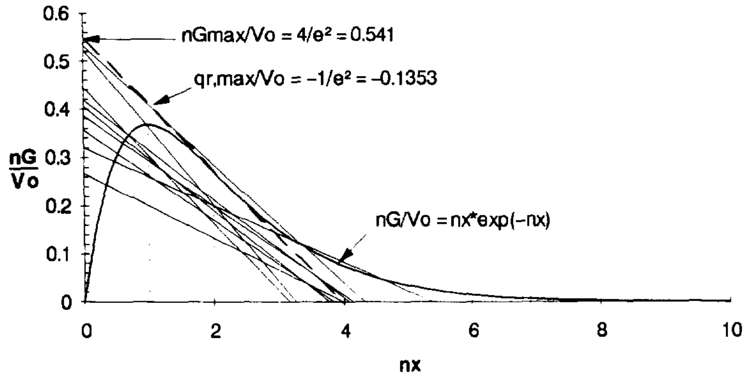

Figure 7. Operational lines for the sedimentation basin 1993-10-13 - 1994-04-20 in a dimensionless solids flux diagram

Operational conditions on nine days during the period 1993-10-13 - 1994-04-20 for the sedimentation basin are shown in figure 7 in a dimensionless solids flux diagram. During this period sludge escape occurred at some occasions. From the figure it may be seen that the value of $nX_r$ was typically around 4, i.e. the value that should be exceeded for the solid flux theory to be valid. For two of the operational lines the limiting solids flux was exceeded and for two of the lines the solids flux was near the maximum flux according to the solids flux theory. The average of the influent and return sludge solids fluxes was used for the operational lines.

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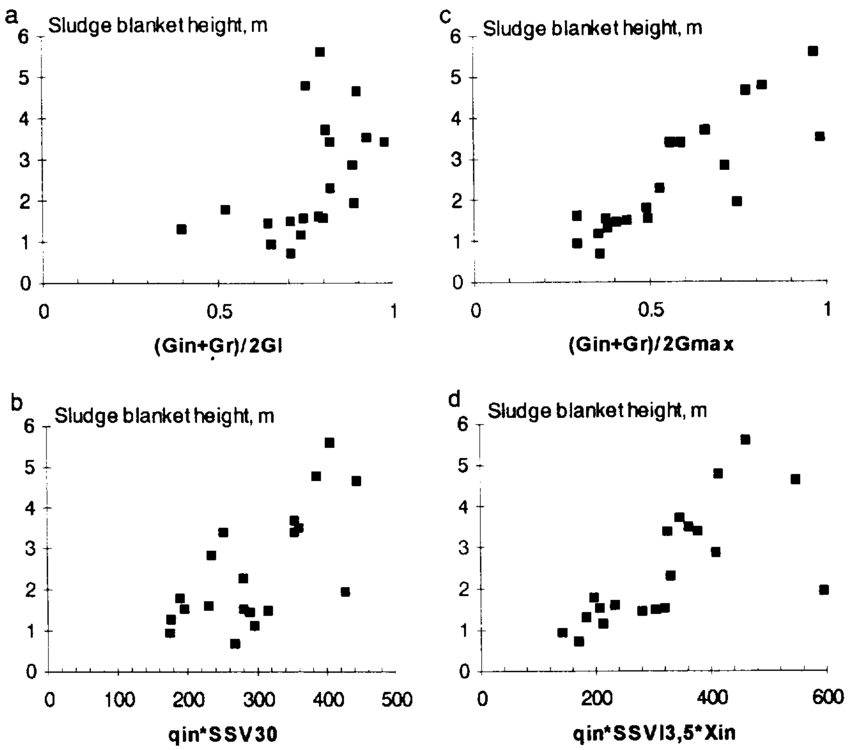

Figure 8. Factors influencing the sludge blanket height.

Different factors were studied that affect the sludge blanket level based on data from twenty days during 1993-05-12 - 1994-04-28 (see Figure 8). The sludge blanket level was above 2 m if the quotient $(G_{in} + G_r)/2G_l$ exceeded a value of about 0.8. (Figure 8a). The limiting solids flux was calculated by use of formula 11. Values above about 4 m of the sludge blanket level were obtained if the quotient of $(G_{in} + G_r)/2G_{max}$ exceeded 0.8 (figure 8b). Increasing values of the products of $q_rSSV_{30}$ and $q_{in}SSVI_{3.5}X_{in}$ increased the sludge blanket levels (Figures 8c and 8d).

## Sludge blanket level and sludge concentration variations

Special studies were made during 1994-03-07 - 1994-03-08 of variations of the sludge blanket and of sludge concentrations in the aeration basin and return sludge. Experimental conditions are shown in Figure 9 for the surface load, the sludge concentration at the end of the aeration basin, the influent solids flux, the height of the sludge blanket, the return sludge concentration and the solids flux in the return sludge. The return sludge flow divided by the sedimentation basin area was constant and equal to 1.23 m/h. The sludge settling properties are shown in figure 5 and the $SSVI_{3.5}$-value was 167 ml/g.

Dynamic simulations of the sludge blanket movements were made by use of the EFOR programme package (Finnson, 1994). The thickening function is based on the Vesilind formula and theories described by Dupont and Henze (1992). It was found that the values of $V_0$ and n were crucial for the result and therefore four different approaches were used:

1. Use of values of $V_0$ and n based on correlation of the sludge index. At the test of sludge blanket movements the $SSVI_{3.5}$ value was 167 ml/g. By use of the Härtel and Pöpel relationships, the value of $V_0$ and n can be calculated to 6.57 m/h and 0.67 $m^3/kg$, respectively.

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2. Experimental determination of $V_0$ and n based on experiments in the Water Research Centre apparatus for the determination of the Stirred Specific Volume Index. Results from such determinations during the test period are shown in figure 5. Obtained values were for $V_0$ 6.58 m/h and for n 0.64 $m^3$/kg.

3. It was assumed that the value of $V_0$ could be rather accurately determined, while the value of n might be sensitive to the size of the apparatus and the stirring conditions. If the sludge blanket is high (as in the test) another strategy is to use the experimentally determined value of $V_0$ (= 6.58 m/h), the value of $q_r$ (1.23 m/h) and calculate the value of n by use of formula 11. The obtained value for n was 0.77 $m^3$/kg.

4. The last strategy was to use the experimentally determined value and adjust the value of n to fit the movement of the experimentally determined sludge blanket level.

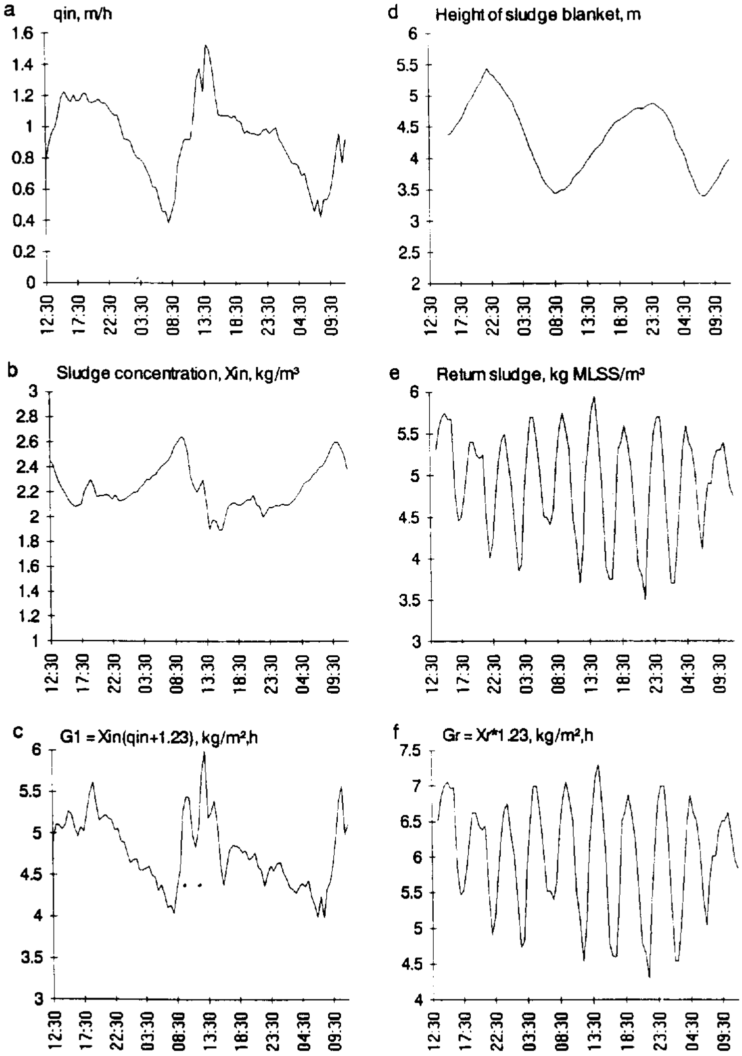

Figure 9. Experimental conditions during the dynamic studies.

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Results of different simulations for $V_0 = 6.58$ m/h and for values of n equal to 0.64, 0.77, 1.1, 1.15 and 1.25 $m^3/kg$, respectively, are shown in figure 10 and compared with the measured sludge height. A good agreement between experimental and simulated values was obtained for n 1.1-1.2 $m^3/kg$.

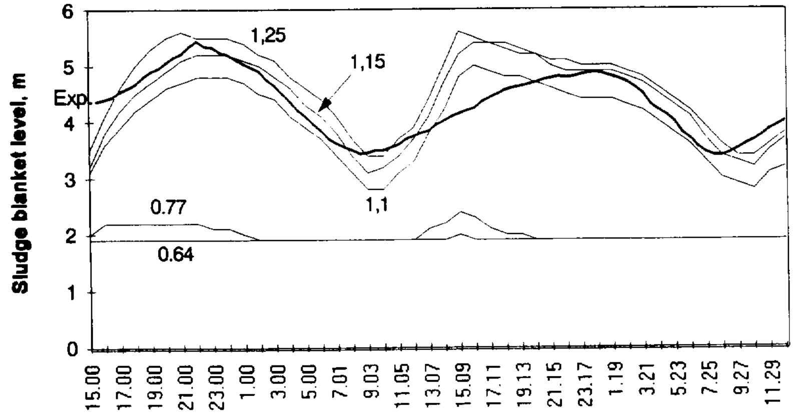

Figure 10. Simulation of sludge blanket level with the EFOR programme.

Simulations were also performed on the variations of return sludge concentration. Figure 11 shows the experimental results and two simulations; $V_0 = 158$ m/d and $n = 0.64$ $m^3/kg$ corresponding to experimental results in Figure 5, $V_0 = 158$ m/d and $n = 1.1$ $m^3/kg$ corresponding to the case with n calibrated near the sludge level.

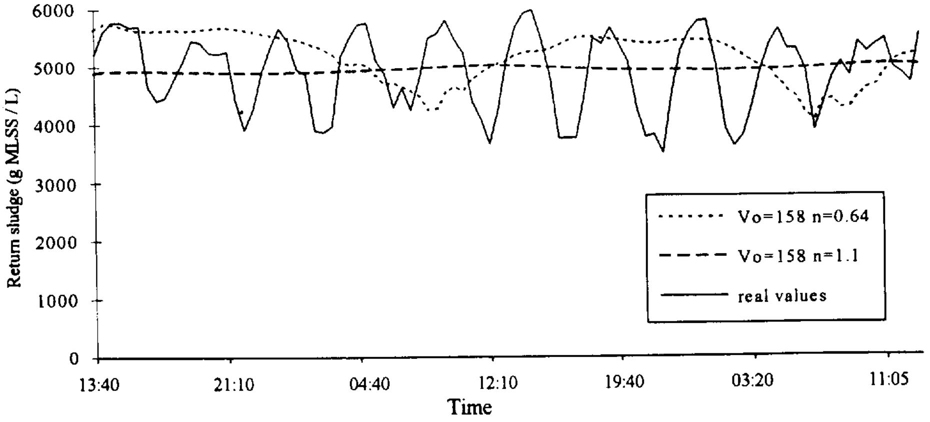

Figure 11. Simulations performed on the variations of the return sludge concentration.

The figure shows that the dynamics of the return sludge were impossible to simulate. The variations of the experimental data reflect the periods of the sludge scrapers, how much sludge had been settled around the individual pumps before they started, the operational interval of the different pumps, etc. These types of variations are not considered in the simulation program. The average value of the return sludge concentration for a longer time period was about the same for all curves. A dynamic model based on the solids flux theory shows that a small variation is obtained in the return sludge concentration if the sludge blanket level is high.

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## DISCUSSION

Implementation of nitrogen removal at Bromma sewage treatment plant means that a higher sludge concentration must be used in the aeration basin. Results have shown that the plant often operates near the critical solids flux and sometimes near the maximum solids flux according to solids flux theory. If the plant is operated at 80% of the maximum flux the influent solids flux must not exceed about $0.43V_0/n$ according to formula 10. The data shown in figure 6 may be described by the formula $V_0/n = 45.3\exp(-0.00822SSVI_{3.5})$. The solids flux should then not exceed $19.5\exp(-0.00822SSVI_{3.5})$ or be below about 13, 8.6 and 5.7 kg/m$^2$,h at $SSVI_{3.5}$ values of 50, 100 and 150 ml/g, respectively. These calculations show the great importance of the $SSVI_{3.5}$ value and the difficulties in implementing nitrogen removal at sludge bulking conditions.

Sludge blanket level measurements may be used to get a better understanding of factors influencing the sludge blanket level and movements. Several factors including unreliable measurement devices and non-ideal behaviour of the sedimentation basin may make it necessary to adjust one parameter to get agreement between measured and calculated data. Figure 11 gives an example of how the sludge settling parameter n is adjusted to fit the sludge blanket level movements. The adjustment could also partly be due to the reason that the values of $nX_r$ and $q_r$ were somewhat below and above, respectively, the values in formulae 8 and 9 for validity of the solids flux theory. Xu *et al.* (1994) found in a similar study that the level of the sludge blanket could be estimated if the values of n and $V_0$ were adjusted. Many applications of the measurement of the sludge blanket level may be foreseen including improved operation of the activated sludge process and on-line characterisation of sludge settling properties.

## CONCLUSIONS

The sedimentation basin at Bromma may be operated at an influent solids flux of about 80% of the limiting solids flux before the sludge blanket gets higher than about 2 m. The stirred specific sludge index has a large impact of the maximum influent solids flux before sludge escape will occur.

Comparisons were made between movements of the sludge blanket level measured in a full-scale sedimentation basin and those simulated using the Danish simulation program EFOR. Different methods were evaluated for the determination of the parameters $V_0$ and n in the Vesilind formula. It was found that no experimental method of determination of $V_0$ and n resulted in a correct simulation of the sludge blanket level.

However, it was possible to accurately simulate the movements of the sludge blanket level by calibrating the value of n. Future research is necessary to find a conversion factor of the parameters determined in simple experiments and values of the parameters in full scale. The program accurately predicted average values of the return sludge concentration but could not predict different dynamical factors due to the operational modes of the sludge scrapers and sludge pumps.

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