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A DYNAMIC MODEL OF THE CLARIFICATION–THICKENING PROCESS

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Abstract—A dynamic model of the clarification–thickening process is presented. Based on the solids flux concept and on a mass balance around each layer of a one-dimensional settler, this model can simulate the solids profile throughout the settling column, including the underflow and effluent suspended solids concentrations under steady-state and dynamic conditions. The model makes use of a special settling velocity equation designed to simulate the settling velocity of dilute and more concentrated suspensions. The model can be applied to both primary and secondary settlers to simulate dynamic and steady-state conditions. Examples based on full-scale and pilot-scale experimental data taken from the literature serve to illustrate the application of the model to secondary settlers. Results of the analysis confirm that the model can serve to predict the effluent and underflow suspended solids concentrations under a variety of conditions.

Key words—clarifications, dynamic modelling, hindered settling, steady-state analysis, solids flux analysis, thickening

NOMENCLATURE

A_c = surface area of the clarifier (m)
J_{dn} = downward solids flux due to the bulk movement of the liquid (g/m-d)
J_j = downward solids flux in layer j (g/m-d)
J_s = solids flux due to gravity settling (g/m-d)
J_{up} = upward solids flux due to the bulk movement of the liquid (g/m-d)
$\min(B, C) = B$ if $B < C$; C if $B > C$
Q_i = influent flow rate to the plant (m³/d)
Q_R = recycle and wastage flow rate (m³/d)
X_{in} = influent suspended solids concentration (g/m³)
X_{min} = minimum attainable suspended solids concentration in the effluent (g/m³)
X_l = lower suspended solids concentration limit of region III (g/m³)
X_u = upper suspended solids concentration limit of region III (g/m³)
X_t = threshold suspended solids concentration (g/m³)
X_j = suspended solids concentration in layer j (g/m³)
f_{ns} = non-settleable fraction of the influent suspended solids
r_p = settling parameter associated with the low concentration and slowly settling component of the suspension (m³/g)
r_h = settling parameter associated with the hindered settling component of settling velocity equation (m³/g)
v_o = maximum theoretical settling velocity (m/d)
v_0' = maximum practical settling velocity (m/d)
v_s = settling velocity (m/d)
α = settling parameter (m³/g)

INTRODUCTION

The separation of solids from water by gravity sedimentation is one of the most important physical processes in a wastewater treatment plant. Solids–liquid separation is a vital component of every biological wastewater treatment system. In the primary clarifier, settleable organic matter is removed by gravity prior to reaching the biological reactor. By design, activated sludge plants transform soluble organic matter into biomass; the effective operation of the process requires that the biomass be removed from the liquid stream (in the secondary settler) prior to being discharged in the receiving waters. Part of the biomass is wasted, while a large fraction is returned to the biological reactor to maintain the appropriate substrate-to-biomass ratio.

Notwithstanding the importance of the solids–liquid separation process, few investigators have proposed a unified settling model designed to address the clarification and thickening functions of settlers. Accordingly, the purpose of this paper is to suggest an alternate form of the settling velocity model, allowing for the development of a unified approach to dynamic modelling of the clarification and thickening functions of settlers.

THE SOLID–LIQUID SEPARATION PROCESS

Depending on the nature and concentration of the solid particles, four types of settling characteristics are normally encountered in a wastewater treatment plant.

Discrete particle settling. Associated with the removal of grit and sand particles, discrete particle settling is characterized by solids which settle as individual entities with little or no interaction with other particles.

Flocculent particle settling. Typical of the type of settling found in primary clarifiers, and the upper layers of a secondary settler, flocculent particle settling is characterized by the flocculation of solid particles as they settle through the water column.

Hindered settling. Suspension in which inter-particle forces hinder the settling process. The mass of particles settles as a unit.

Compression settling. "Settling" is achieved by compression of the mass of particles. Compression results from the weight of particles added to the system.

Clarification

The theory of discrete particle settling has been rigorously addressed (Camp, 1945). Given the fact that the solids concentration in the upper layers of the clarifier is sufficiently low to result in discrete particles, one would think that this theory can readily be extended to the clarification component of primary and secondary settling basins. However, the problem does not lie with the settling velocity theory, but with the flocculent nature of these particles which affects the particle size distribution from one layer to another. Li and Ganczarczyk (1987) have found the settling velocity of activated sludge floc particles to be a linear function of their cross-sectional diameter. However, little effort has been made so far to predict the size distribution of the solids particles in the upper layers of a secondary clarifier as a function of the operational characteristics of the activated sludge process. Roth and Pinnow (1981) are among the few investigators that have examined the particle size distribution of secondary clarifier effluent from activated sludge plants. Consequently, a direct application of the discrete particle settling theory to the primary and secondary clarification functions is premature.

Most of the clarification models reported in the literature are based on a statistical analysis of full-scale plant data, relating the effluent suspended solids concentration to a number of process parameters such as mixed-liquor suspended solids (MLSS), recycle flow rate, overflow rate, change in overflow rate, detention time, air flow rate in the biological reactor, etc. Chapman (1984) and Hill (1985) provide a good review of the more popular models.

Thickening

As the concentration of solids increases, the mass of solids tends to settle as a unit. The settling velocity of the sludge blanket has been found to be a nonlinear function of the solids concentration. Hill (1985) provides a comprehensive review of the many settling velocity models applicable to the thickening function of the settler.

The solids handling capacity of a settler can be assessed by performing a limiting solids flux analysis (Keinath *et al*., 1977). In a continuous flow settler, the downward solids flux is the sum of the gravity settling flux (J_s) and the solids flux due to the bulk movement of the liquid (J_{dn}), namely the underflow:

$$J = J_s + J_{dn} \tag{1}$$

$$J_j = X_j v_{sj} + X_j v_u \tag{2}$$

where J_j = downward solids flux in layer j; J_s = gravity settling flux; J_{dn} = settling flux due to the bulk movement of the liquid; X_j = solids concentration in layer j; v_{sj} = settling velocity of the solids in layer j; v_u = underflow velocity. Dick and Ewing (1967), Vesilind (1968) and Keinath *et al.* (1977) have described in detail the thickening theories under steady-state conditions.

Dynamics of the solids–liquid separation processes

Bryant (1972) was one of the first to develop a dynamic model of the activated sludge process, including solids–liquid separation models for both the primary and secondary settlers. Based on a variable thickness/variable number of layers concept, Bryant developed a complex set of heuristics to govern the fate of the physical dimensions of a layer within the secondary clarifier (i.e. the layer's appearance and disappearance depending on its thickness). Bryant's model of the primary settler was not as sophisticated and was based on a sequence of five continuous flow stirred tank reactors (CFSTR), selected in such a way as to replicate the appropriate detention time for the system (e.g. 1.5–2.0 h in his case).

Busby (1973), Stenstrom (1976) and Hill (1985) have all made significant efforts to improve our understanding of the dynamics of the thickening process using the solids flux theory in a one-dimensional layered settler. While Bryant and Busby made use of a variable number of layers of time-varying thickness, Stenstrom and Hill used a fixed number of layers of constant thickness to describe the thickening function of settlers.

Recently, Vitasovic (1986, 1989) developed a more rigorous analysis of the dynamics of secondary settlers, that included consideration of the upward bulk movement of the liquid in the layers above the feed point. Our approach, described briefly in the next section, is based on the work of Vitasovic (1986).

However, before focusing on the development of the model, it should be emphasized that all of the solids–liquid separator models referenced so far have failed to provide a unified framework to predict the suspended solids in the effluent of the clarifier. In all cases, authors have made use of statistically-based models to predict the effluent suspended solids. While this approach might seem logical, it fails to account for a rigorous solids balance in the settler. The problem can be particularly important as settlers reach failure.

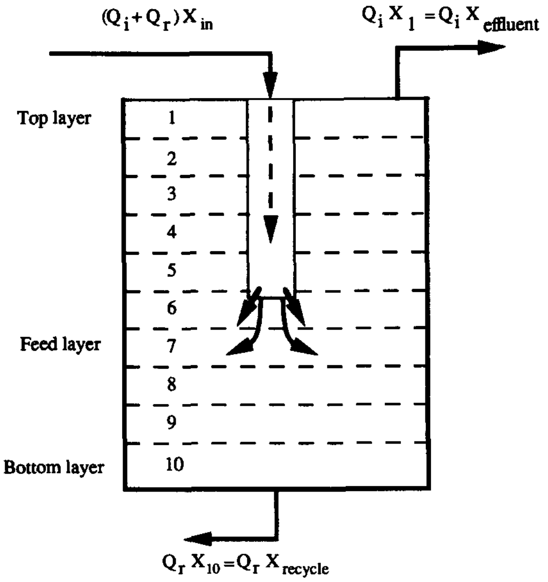

Fig. 1. Layered settler model.

LAYERED SETTLER MODEL

Vitasovic's (1986) model predicts the solids concentration profile in the settler by dividing the settler into a number of layers (10) of constant thickness as shown in Fig. 1, and by performing a solids balance around each layer. Vitasovic's model falls in the same class of one-dimensional models as those of Bryant (1972), Busby (1973), Stenstrom (1976) and Hill (1985). All of them, including the one presented in this paper, are based on the following assumptions:

- incoming solids are distributed instantaneously and uniformly across the entire cross-sectional area of the clarifier layer; and
- only vertical flow is considered in the model.

Vitasovic's model does not include a clarification component. Consequently, effluent suspended solids are not predicted during normal operating conditions. However, when the settler's thickening and/or storage function fails, the model will predict large quantities of effluent suspended solids. Vitasovic (1986) arbitrarily defines the sludge blanket height as the height of the first layer with a solids concentration greater than 3000 mg/l.

Five different groups of layers are present in the proposed model, depending on their position relative to the feed point. Table 1 summarizes the input and output of solids to each group of layers, while the solids balance around each type of layer is summarized in Fig. 2.

Vitasovic's model is based on the traditional solids flux analysis, with the exception of the threshold concentration (X_t) designed to limit the downward flux of solids to that which can be handled by the layer below. For example, above the feed layer the flux out of layer "j" is restricted, if the concentration in layer "$j+1$" is greater or equal than some threshold value (X_t), in which case the flux out of layer "j" is set equal to the $\min[J(j), J(j+1)]$. The specifics of the algorithm are summarized in Fig. 2.

The solids flux due to the bulk movement of the liquid is straightforward to assess, being equal to the product of the concentration (X) and the bulk velocity of the liquid (v_b), which can be up or down depending on the position of the layer with respect to the feed point.

The solids flux due to gravity settling of the solids particles is given as the product of the concentration (X) and the settling velocity of the solids particles (v_s). As indicated previously, several models have been suggested to describe the settling velocity of a mixed-liquor. One of the more widely accepted settling velocity model is that of Vesilind (1968):

$$v_s = v_0 e^{-\alpha X} \tag{3}$$

where v_s = settling velocity of the suspension; v_0 = maximum settling velocity; X = solids concentration; and α = model parameter. This model was used successfully by Hill (1985) and Vitasovic (1986).

However, it should be recognized that Vesilind's settling velocity equation applies only to hindered settling conditions. As the solids concentration in the upper layers of the clarifier decreases below the hindered settling concentration, settling velocities predicted by Vesilind's equation will exceed the actual settling velocity of the floc particles as predicted by Li and Ganczarczyk (1987).

In a well operating settler, the concentration of solids in the upper layers of a clarifier increases with depth. Because of the dynamic forces acting on the floc particles above the feed point, the particle size distribution of the floc particles changes from one layer to another. In their study on particle size distribution, Roth and Pinnow (1981) found that floc particles in the effluent of secondary clarifiers from activated sludge plants, followed a log-normal distribution. More recently, Patry and Takács (1991) have

Table 1. Layered settler model: input–output summary

Layer	Input: Feed	Input: Settling	Input: Bulk liquid flux	Output: Settling	Output: Bulk liquid flux
Top layer	–	–	Up	+	Up
Layers above feed point	–	+	Up	+	Up
Feed layer	+	+	—	+	Up–down
Layers below feed point	–	+	Down	+	Down
Bottom layer	–	+	Down	–	Down

Note: + = phenomenon considered; – = phenomenon not considered.

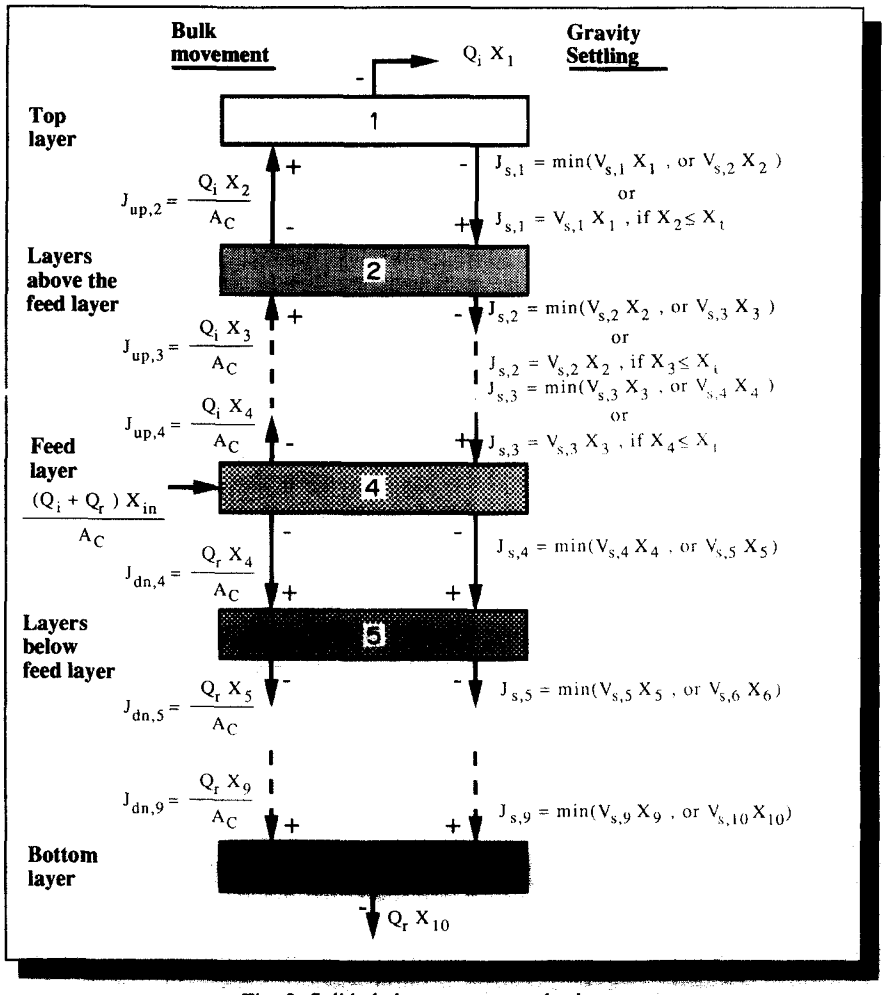

Fig. 2. Solids balance across settler layers.

derived a relationship between particle size distribution, described by the mean and variance of the log of the particle diameters, and their concentration. A similar expression was also derived for the average settling velocity of a flocculent suspension in the upper layers of a secondary clarifier. Finally, because of the operational constraints of a secondary clarifier, Patry and Takács have shown that the average settling velocity of solids in the upper layers of a secondary clarifier could be related to its concentration. Consider for example a layer in the upper portion of a secondary clarifier having a log-normal particle size distribution. As the overflow rate increases, particles with a higher settling velocity (i.e. larger particle diameter) will be fluidized and carried upward. Because particle size is bounded at zero, this will result in a larger mean and variance in the log of the particle diameters. Based on the relationship derived by Patry and Takács (1991), the increase in overflow rate will result in a larger solids concentration, as would have normally been expected from an increase in overflow rate. However, an increase in the mean and variance of the log of the particle diameters will also result in an increase in the average settling velocity of the suspension as depicted in region II of Fig. 3.

From a practical standpoint, the correlation between average settling velocity and solids concentration (region II, Fig. 3) is valid for low solids

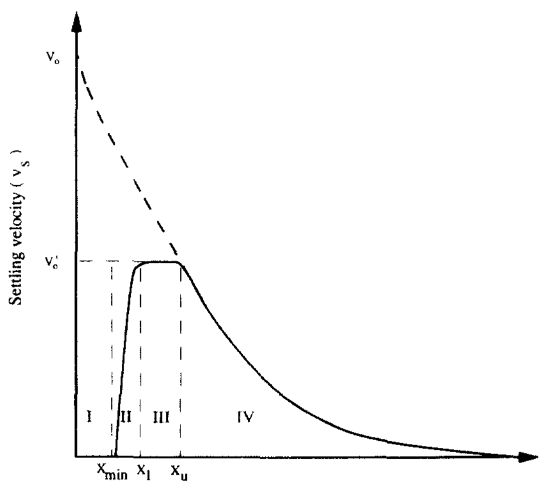

Fig. 3. Settling velocity model.

concentration. As the solids concentration increases, a region exists (region III, Fig. 3) where the average settling velocity of the suspension reaches a maximum upper limit. This corresponds to the transition zone between the low solids concentration region (region II) and hindered settling conditions (region IV). Ossenbruggen and McIntire (1990) have also suggested that a maximum practical settling velocity be used below the hindered settling concentration. Assuming maximum floc particle diameters of 1–2 mm in this concentration range would result in floc particle settling velocities in the range of 175–400 m d^{-1} (Li and Ganczarczyk, 1987).

Mathematically, the generalized settling velocity model can be represented as the sum of two exponential terms:

$$v_{sj} = v_0 e^{-r_h X_j^*} - v_0 e^{-r_p X_j^*} \tag{4}$$

$$0 \leqslant v_{sj} \leqslant v_0' \tag{5}$$

where v_{sj} = settling velocity of the solids particles in layer j(m/d); v_0 = maximum settling velocity (m/d); r_h = settling parameter characteristic of the hindered settling zone (m^3/g); r_p = settling parameter characteristic of low solids concentration (m^3/g); $X_j^* = X_j - X_{min}$; X_j = suspended solids concentration in layer j(g/m^3); X_{min} = minimum attainable suspended solids concentration (g/m^3); $X_{min} = f_{ns} X_{in}$; X_{in} = mixed-liquor suspended solids entering the settler (g/m^3); f_{ns} = non-settleable fraction of X_{in}. As depicted in Fig. 3, v_{sj} reaches a maximum value of v_0' in the range of $X_l - X_u$, where X_l and X_u represent the lower and upper concentrations of region III, respectively.

The first term ($v_0 e^{-r_h X_j^*}$) in equation (4) reflects the settling velocity of the large, well flocculating particles. On the other hand, the second term ($v_0 e^{-r_p X_j^*}$) of equation (4) is a velocity correction factor to account for the smaller, slowly settling particles.

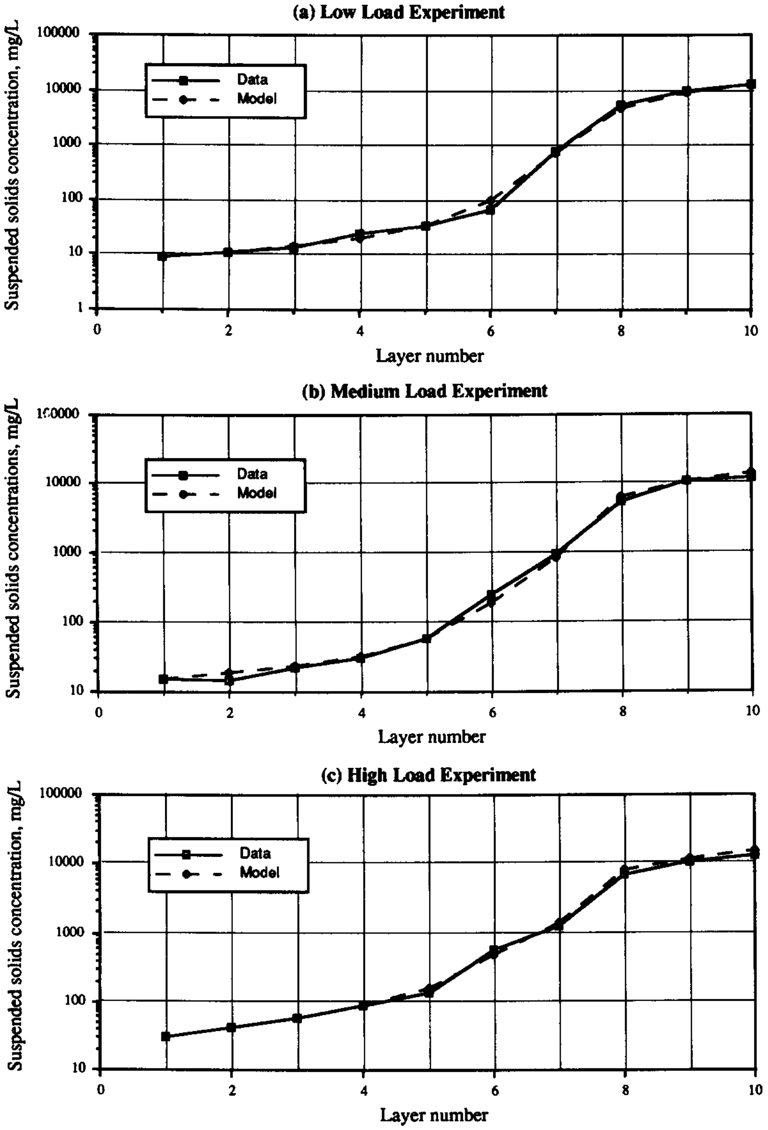

Fig. 4. Observed and simulated concentration profiles.

Four regions are of interest in equation (4):

$\boxed{X < X_{min}}$

In this region, the settling velocity is set equal to zero, as the suspended solids concentration reaches the minimum attainable concentration.

$\boxed{X_{min} < X < X_l}$

In this region, the settling velocity is dominated by the slowly settling particles; in this case, v_s is most sensitive to r_p.

$\boxed{X_l < X < X_u}$

In this concentration range (typically between 200–2000 g/m^3) the settling velocity is independent of concentration. Floc particles reach their maximum size resulting in an average settling velocity that is more or less independent of concentration (v_0').

$\boxed{X > X_u}$

In this region, the effect (correction factor) of the slowly settling particles is small in comparison to the total settling velocity. The settling velocity is most sensitive to r_h and the model effectively reduces to Vesilind's equation.

This settling velocity model was found to produce realistic estimates of the effluent and underflow suspended solids concentration under both steady-state and dynamic conditions.

Assessing model parameters

In this study model parameters were assessed based on an analysis of field and pilot-scale experimental data. In all cases, SIMUSOLV (Steiner *et al.*, 1987), a non-linear dynamic optimization package was used for model parameter identification.

Alternatively, model parameters of the proposed settling velocity model could be assessed through a combination of laboratory experiments and non-linear optimization techniques (Kennedy, 1991). For example, f_{ns}, the minimum effluent suspended solids can readily be measured in a settling column analysis. An estimate of the maximum practical settling velocity, v_0', can be obtained by diluting the mixed liquor to 1–2 g/l, and measuring the settling velocity of the large individual floc particles. Vesilind's hindered settling velocity model parameters, v_0 and r_h, can be measured through a series of column settling tests (Vesilind, 1968; Keinath *et al.*, 1977). Finally, r_p is best assessed using a non-linear optimization search technique, such as the one considered in this study.

APPLICATION OF THE MODEL

Two examples will serve to illustrate the application of the settling velocity model. In the first example, the model will be applied to full-scale data collected by Pflanz (1969) assuming that steady-state conditions prevailed at the time of the experiments. In the second example, dynamic data collected at pilot scale (Thompson, 1988) will be used to assess the potential of the model under transient conditions.

Pflanz full-scale data

Pflanz (1969) carried out experiments to determine the settling characteristics of sludges under different conditions. In one of his experiments at Celle, he provided solids profiles in a final settling tank with sufficient detail to calibrate the model presented earlier.

The high-rate activated sludge treatment plant received mainly domestic wastewater. Pflanz measured the suspended solids concentrations at seven points along the radius of the circular secondary settler and at ten points along its depth. For the purpose of this analysis, the two-dimensional suspended solids concentration data base was filtered and the data weighted with respect to the cross-sectional area of the clarifier prior to being reduced to one-dimensional solids profiles. A summary of the characteristics of the three experimental conditions conducted by Pflanz is presented in Table 2.

The settler model was coded in ACSL (Advanced Continuous Simulation Language), a continuous simulation language developed by Mitchell & Gauthier (1986). Model parameters were estimated using SIMUSOLV, an integrated multi-functional parameter estimation and optimization package coupled to ACSL (Steiner *et al.*, 1987). SIMUSOLV was used to identify a consistent set of model parameters for each of the three data sets.

Results of the analysis are presented in Fig. 4(a–c), where the logarithm of the solids concentration is plotted as a function of depth. A logarithmic scale was chosen for the solids concentration to provide more detail at lower concentrations. Model parameters for each of the three events are shown in

Table 2. Summary of the experimental conditions (Pflanz, 1969)

Experiment	Flow (m^3/h)	Detention time (h)	Sludge return (m^3/h)	Suspended solids Input (g/l)	Suspended solids Recycle (g/l)	Mass of SS Loading (t/d)	Mass of SS Output (t/d)
Low load	360	5.0	300	5.62	12.87	89.0	92.8
Medium load	450	4.0	300	5.52	12.80	99.4	92.3
High load	600	3.0	300	5.10	14.72	110.2	106.2

Table 3. Model parameters fitted to Pflanz full-scale data sets

Parameter	Low load	Medium load	High load
v_0 (m/d)	214.2	370.0	172.8
v_0' (m/d)	150.2	142.9	112.1
r_p (m^3/g)	5.71×10^{-3}	2.86×10^{-3}	2.70×10^{-3}
r_h (m^3/g)	3.64×10^{-4}	3.78×10^{-4}	2.93×10^{-4}
f_{ns} (—)	1.23×10^{-3}	2.28×10^{-3}	2.59×10^{-3}
inp(6) (—)	0.00	0.11	0.24
inp(7) (—)	1.00	0.89	0.76

Note: inp(6) and inp(7) represent the fraction of the feed distributed to the sixth and seventh layers, respectively, with inp(6) = 1 − inp(7).

Table 3 while results of the simulation are presented in Table 4.

Based on the results of the analysis, it is apparent that the effluent suspended solids predictions are excellent—deviating from the recorded values by approx. 1% (i.e. a maximum of 0.1 g/m^3). In general, the underflow concentration is also very well simulated by the model. Deviations of 1.1, 13.8 and 18.2% from the observed underflow concentrations have been recorded for the low, medium and high load conditions, respectively. The largest discrepancies between observed and simulated solids concentrations are found around the feed layer.

However, in assessing the results of the simulation it should be emphasized that the details surrounding Pflanz's experiments were not available from the published reports. For example, in simulating the low, medium and high load conditions, steady-state conditions had to be assumed for each of the three events. It is easy to verify that this assumption is not strictly valid for the experiments, as the mass of solids entering the clarifier is larger than the mass of solids leaving the settler (i.e. 3–7 tonnes/d). Accordingly, for the medium and high load conditions, the model was forced to overpredict the underflow concentrations because this was necessary to reach steady-state. Notwithstanding this discrepancy, the model was able to replicate the general behaviour of the solids profile for all three experiments. In addition, the model was able to predict the depth of the sludge blanket measured by Pflanz.

While model parameters varied from one condition to another, the range of values is not unrealistically large given the limited data available.

Feed distribution to the clarifier. In his paper, Pflanz did not provide sufficient details about the physical characteristics of the settler to properly assess the feed distribution to the settler. However, an analysis of the concentration profiles reveals that the feed layer must have been above the eighth layer where zone settling conditions prevailed. Similarly, the feed layer had to be below the fifth layer because of the low solids concentration in and above the fifth layer. Accordingly, the sixth and seventh layers were considered as potential feed point layers. The feed distribution between layers is a function of the hydraulic regime. While the proposed model does not pretend to simulate the dynamics of feed point distribution, it does allow the flexibility to handle multiple feed layer conditions, to reflect more closely field conditions. Optimized results are shown in Table 3. As it turns out, most of the feed had to be distributed to layer 7. However, as the hydraulic load increased, a larger fraction of the feed had to be distributed to layer 6.

Pilot-scale experiments

Thompson (1988) investigated the benefits of step feed in reducing the impact of storm flows, using the 288 m^3/d pilot plant located at the Wastewater Technology Centre in Burlington (Ontario, Canada). Using his data, efforts were made to calibrate the settling velocity model under dynamic conditions.

The pilot plant consists of three aeration tank-in-series followed by a final settler. Settled sewage entering the plant can be fed to any of the three reactors. The secondary settler has a sidewater depth of 2.7 m, while the overflow rate to the settler was set to 27.6 m/d. A constant recycle was used in the study. The characteristics of the plant are summarized in more detail by Thompson (1988).

A mathematical model of the pilot plant was constructed using a library of dynamic models developed by Patry and Takács (1990). The biological reactors were modelled using the IAWPRC Task Group model of the activated sludge process. Details of the model are given elsewhere (Henze *et al.*, 1987). The settler model described earlier was coupled to the activated sludge model providing a complete representation of the pilot plant.

No major calibration was needed for the activated sludge portion of the model, however parameters of

Table 4. Observed and simulated suspended solids concentrations (g/m^3)

	Suspended solids concentration (g/m^3)								
	Low load			Medium load			High load		
Layers	Observed	Simulated	% Diff.	Observed	Simulated	% Diff.	Observed	Simulated	% Diff.
1	9.0	9.1	1.1	15.6	15.7	0.6	30.7	30.8	0.3
2	10.7	11.2	4.7	14.8	18.9	27.7	41.4	42.9	3.6
3	13.6	14.1	3.7	21.8	23.6	8.3	59.4	58.5	1.5
4	23.8	19.5	18.1	29.9	32.9	10.0	88.6	87.4	1.4
5	35.0	33.8	3.4	58.8	59.2	0.7	135.5	163.5	20.7
6	66.6	96.6	45.0	274.2	187.4	24.2	567.7	481.1	15.3
7	787.1	706.7	10.2	933.0	826.0	11.5	1273.6	1377.6	8.2
8	5280.8	4618.9	12.5	5263.6	6130.3	16.5	6999.4	8308.6	18.7
9	10021.5	9124.4	9.0	10481.9	10699.6	2.1	10613.5	11901.0	12.1
10	12487.2	12353.1	1.1	12100.1	13766.5	13.8	12893.0	15238.4	18.2

the settling velocity model were adjusted to reflect more closely the actual behaviour of the secondary clarifier. The calibrated set of model parameters are:

$$v_0 = 712.0\ \mathrm{m/d};$$

$$v_0' = 340.0\ \mathrm{m/d};$$

$$r_h = 4.26 \times 10^{-4}\ \mathrm{m^3/g};$$

$$r_p = 5.0 \times 10^{-3}\ \mathrm{m^3/g};$$

and $$f_{ns} = 1.0 \times 10^{-4}.$$

The model was verified against two sets of experiments: (a) storm flow conditions without step feed; and (b) storm flow conditions with step feed to the second reactor. The analysis focused on the solids distribution within the settler, the sludge blanket height, and the effluent suspended solids.

Storm flow conditions without step feed. Results of the simulation under storm flow conditions without step feed are shown in Fig. 5(a) and (b) and compared with the recorded observations. Storm flow conditions were simulated by an abrupt change in flowrate from 200 to 500 l/s, while the recycle flowrate was kept constant. This produced an increase in the sludge blanket height (H_s) and consequently a high effluent suspended solids value once the sludge blanket reached the weirs [Fig. 5(b)].

As observed by Thompson (1988), the effluent suspended solids concentration (ESS) is relatively

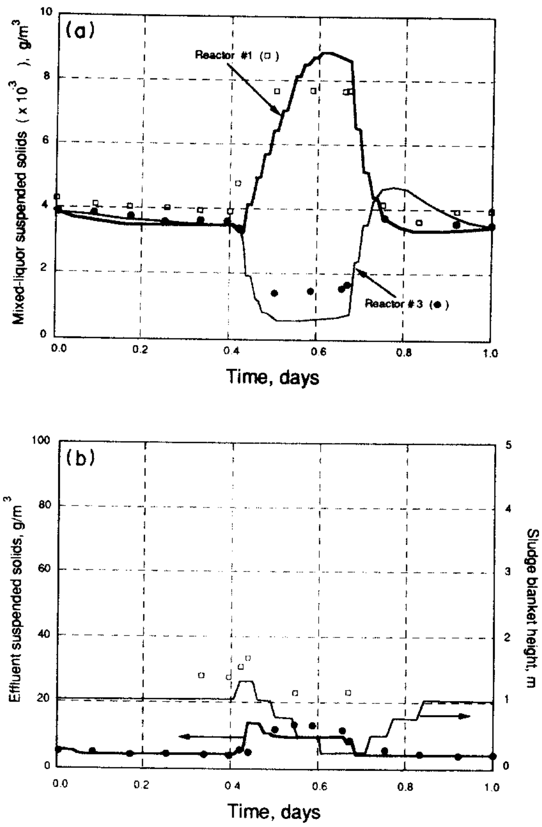

Fig. 6. Storm flow with step feed to second reactor.

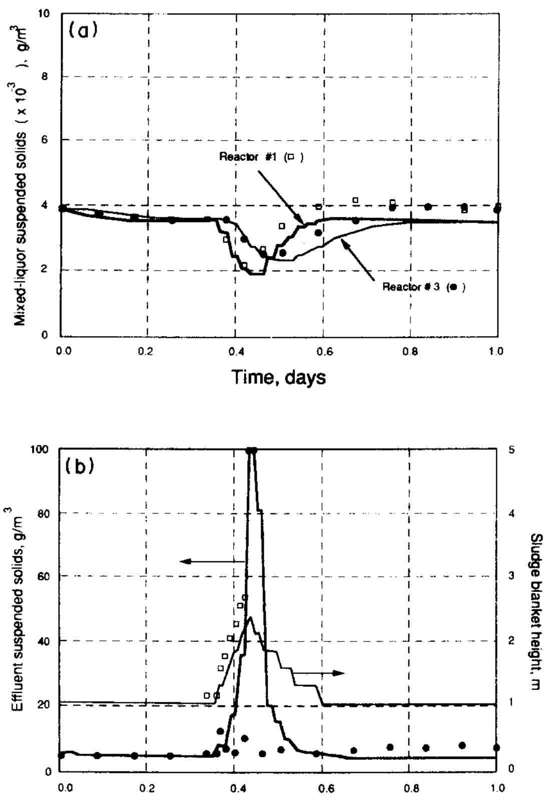

Fig. 5. Strom flow without step feed.

independent of the sludge blanket height until the moment the blanket reaches the weir level. The sludge blanket, as well as the effluent suspended solids concentration, returned to their normal levels once normal flow conditions were re-established. The solids concentration in the reactors was drastically reduced during storm flow. A 40% reduction in the MLSS concentration in each reactor was observed in the model [Fig. 5(a)]. This reduction is in close agreement with Thompson's results. The mixed-liquor suspended solids in the first and third reactors are plotted in Fig. 5(a). The decrease in the MLSS concentration is well simulated—however the recovery is underestimated by the model. A possible explanation for this discrepancy lies in the fact that the mass of solids lost from the settler during storm flow is not known precisely. Accordingly, it is possible that the actual mass of solids washed out from the pilot plant could have been significantly smaller than that predicted by the model.

Storm flow conditions with step feed to the second reactor. To prevent a significant loss of solids during storm flow conditions, Thompson (1988) experimented with a number of step feed control measures. In this particular set of experiments, the operational strategy was to step feed the settled sewage to the second reactor during storm flow conditions. The simulated and observed results are shown in Fig 6(a) and (b).

As shown in Fig. 6(a), the first reactor was used to store the biomass during the storm, while solids from the third reactor were washed out, decreasing the solids loading to the settler. Initially, the height of the sludge blanket rose slightly, however this tendency was soon reversed [Fig. 6(b)]. Simulated and measured effluent suspended solids are in close agreement.

In general, the model was able to replicate fairly closely the trends in MLSS, effluent suspended solids, and sludge blanket height under a variety of dynamic events. The discrepancies between the observed and simulated results fall within the expected range of accuracy for such complex models. It should be noted, that Thompson's experiments were not initially designed for dynamic modelling purposes. Accordingly, a full solids profile and balance were not available for this investigation.

CONCLUSIONS

A multi-layer dynamic model of the clarification/thickening process was presented. Based on the solids flux concept and a mass balance around each layer of a one-dimensional settler, the model is designed to predict the solids profile along the settling column, including the effluent and underflow suspended solids. The model provides a unified framework for the simulation of the clarification and thickening processes under both steady-state and dynamic conditions. The model was applied to both pilot scale and full scale experimental data with very good results.

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