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Comparison of one-dimensional secondary settling tank models

ABSTRACT

The secondary settling tanks (SST) often prove to be the bottleneck of the whole activated sludge wastewater treatment process. Therefore, when using computer simulation for the design and optimal operation of wastewater treatment plants, the SST model has to be selected adequately besides the model describing the activated sludge process. For this reason, six SST models are introduced and compared in this study using the framework of the Simulation Benchmark developed by the COST 682 group. The Takács-model is described in the Benchmark in detail, combination of it with the Härtel–Pöpel correction function is investigated is this study. The models of Otterpohl and Dupont having three component fractions, the model of Hamilton which adds a diffusion term to the convective process description and a reactive SST model are also simulated and analysed in this contribution.

KIVONAT

Az utóülepítés gyakran a komplett eleveniszapos szennyvíztisztítási folyamat legkritikusabb része. Így a telepek tervezéséhez és üzemeltetéséhez alkalmazott számítógépes szimuláció során az eleveniszapos eljárás modellje mellett fontos az utóülepítő modelljének megfelelő megválasztása is. Ezért munkánkban hat egydimenziós ülepítőmodellt szimuláltunk és hasonlítottunk össze felhasználva a COST 682 projekt keretében elkészült szimulációs protokollt.

KEYWORDS

Secondary settling tank; one-dimensional modelling; dynamic simulation; gravity sedimentation

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INTRODUCTION TO SECONDARY SETTLING TANKS

In the activated sludge process, the biological sludge mass has to be separated from the treated water to produce clear final effluent. This solid-liquid separation process is usually achieved by gravity sedimentation in traditional secondary settling tanks (SSTs, often referred as secondary settlers, final clarifiers or secondary thickeners).

From the biological reactor the mixed liquor enters the secondary clarifier where it should be sufficiently clarified in order to produce an effluent of acceptable quality. The sludge should also be adequately thickened so that the desired solids level in the bioreactors can be maintained through sludge re-circulation. Furthermore, secondary settlers should function as storage tanks to store sludge under high solids loading rate and high surface overflow rate typically under peak wet weather conditions. Should any of these functions fail, suspended solids (SS) will be carried over the effluent weirs and escape with effluent. Besides the resulting poor effluent quality, excessive loss of SS may result in the decrease of mixed-liquor suspended solids and hence the sludge age, what affects the whole biological process (e.g. nitrogen removal efficiency can significantly decrease).

The behaviour of the secondary settler in its clarification, thickening and storage function is influenced both by the settling tank design features (e.g. flow rate, inlet arrangement) and the conditions in the biological reactor. For example, under-aeration can decrease the settleability and thickenability of the sludge owing to the proliferation of filamentous bacteria, which leads to bulking. However, over-aeration can lead to poor flocculation and pinpoint floc formation, which result in poor clarification even though the sludge might otherwise have good settling characteristics. Therefore, the functions of the SST and biological reactor are closely related to each other, so the design and operation of one cannot be undertaken independently of the other. Mathematical modelling used for plant design and operation also has to take into account the physical and biological processes in the SST since practical experience showed that that the SST is often the main bottleneck of the entire activated sludge process.

ONE-DIMENSIONAL SECONDARY CLARIFIER MODELS

Common one-dimensional models are based on the flux theory. It is assumed that in clarifiers the profiles of horizontal velocities are uniform and that horizontal gradients in concentration are negligible. Consequently, only the processes in the vertical dimension are modelled. The resulting idealized settling cylinder is treated as a continuous flow reactor. Figure 1 shows the flow scheme. At the inlet section, the inflow and the introduced suspensions are homogeneously spread over the horizontal cross section and the suspension is diluted by convection as well as other transport processes. The flow is divided into a downward flow towards the underflow exit at the bottom, and an upward flow towards the effluent exit at the top. Both liquid and suspended solids enter the cylinder through the inlet cross section and are withdrawn at the bottom and at the top.

Further assumptions are also taken into consideration:

- The concentration of SS is completely uniform within any horizontal plane within the settler;
- The bottom of the solids-liquid separator represents a physical boundary to separation and the solids flux due to gravitational settling is zero at the bottom;
- There is no significant biological reaction affecting the solids mass concentration within the separator.

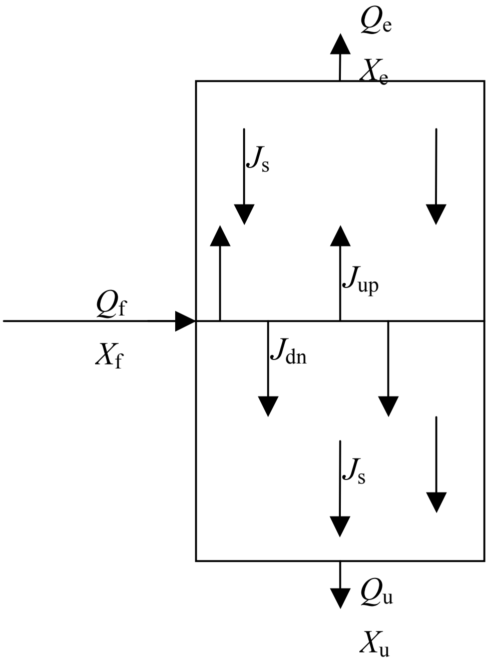

Figure 1: Flux directions of the one-dimensional SST model approach

The surface area A and the volume of the clarifier to be modelled, and consequently the surface overflow rate $q = Q/A$ and the hydraulic detention time, are taken from the prototype. Under steady-state conditions the flow and mass balances are:

$$Q_F = Q_E + Q_R$$
$$Q_F X_F = Q_E X_E + Q_R X_R$$

with Q and X as flow rate and SS concentration, respectively, and the subscripts F, E and R for feed, effluent and recycle, respectively.

The transport of solids take place via the bulk movement of the water relative to the side wall and the settling of the sludge relative to the water. The total flux J_T consists of the bulk flux $J_B = v\mathrm{X}$ and the settling flux $J_s = v_s X$ and becomes

$$J_t = vX + v_s X$$

where v denotes the vertical bulk velocity, v_s the settling velocity of the sludge and X the sludge concentration. The form of differential conservation equation describing this process is:

$$-\frac{\partial X}{\partial t} = v\frac{\partial X}{\partial y} + \frac{\partial v_s X}{\partial y}$$

with t as time and y as vertical coordinate with the origin at the surface. The two terms on the right-hand side refer to the bulk flux and the settling flux. This equation does not include any inlet source or outlet sinks. Assuming constant horizontal cross section A over the entire depth, the bulk velocity v is only dependent on whether the observed cross section is in the overflow region over the inlet position or in the underflow region.

The flux theory is made operational in computer programs by splitting up the tank into a number of horizontal layers and by discretizing the differential conservation equation on these layers. A number of empirical settling velocity functions have been proposed in literature, majority of the functions are based either on the exponential ($v_s = ke^{-nX}$) or the power function ($v_s = kX^{-n}$).

The Takács-model

The most widely used model is that of Takács who based his work on the Vesilind model [14.] but suggested a new so-called *double-exponential* settling velocity which is capable of predicting the effluent SS concentration more realistically than the exponential function of Vesilind [13.]. He based his results on the measurements of the Pflanz full scale data [11.]. The double-exponential settling velocity function proposed by Takács *et al.*:

$$v_s(X) = \max\left\{0, \min\left\{v_0', v_0(\exp^{r_h(X-X_{\min})} - \exp^{r_p(X-X_{\min})})\right\}\right\}$$

where v_0 and v_0’ are the maximum theoretical and practical settling velocity, respectively, r_h and r_p are the hindered and flocculant zone settling parameters. $X_{\min}$ is the minimum attainable suspended solids concentration in the effluent and is a function of the influent SS concentration to the settler:

$$X_{\min} = f_{ns} X_f$$

where f_{ns} is the non-settleable fraction of X_f. The inclusion of X_f will directly influence the behaviour of the settler, especially within the clarification zone. While Abusam and Keesem showed that parameters have little effect on SS in the underflow [1.], at higher load the hindered settling parameter will determine the compactibility of the sludge, the return concentration that can be achieved and the loading when the clarifier will fail.

The function divides the settling velocity into four regions in order to describe the behaviour of the different sludge fractions (unsettleable fraction, slowly settling fraction, rapidly settling fraction). For $X < X_{\min}$ the settling velocity is zero since in this case the concentration is under minimum achievable effluent SS concentration. When $X_{\min}<X<X_{\mathrm{low}}$ the settling velocity is dominated by the slowly settling particles. For low concentrations of SS, Patry and Takács showed that the mean particle diameter increases as the solids concentration in the free settling zone of the clarifier gets higher [10]. An increasing particle diameter implies a higher settling velocity and this effect is reflected in the behaviour of the settling velocity within the region $X_{\min}<X<X_{\mathrm{low}}$. When $X_{\mathrm{low}}<X<X_{\mathrm{high}}$ (usually from 200 to 2000 g/m^3) the settling velocity is considered to be independent of the concentration as the flocs reach their maximum size. Finally, when the SS concentration grows above X_t the model uses the traditional exponential velocity function describing the effects of hindered settling.

The original model proposed by Takács *et al.* does not take into account the effect of sludge volume index (SVI) explicitly, however, incorporation of SVI is possible through the modification of the settling velocity parameters. E.g. r_h can be estimated with a correlation between SVI and r_h ($r_h = a + b\,SVI + c\,SVI^2$ where a, b, c are the SVI correlation coefficients).

The Härtel correction function

In the proposal of Härtel and Pöpel a correction of the settling function was suggested besides the boundedness of the settling flux to that of the lower layer [5]. The correction function is based on empiricism and is dependent on SVI, the vertical position (y), the position of the inlet layer (h_0) and the feed solids concentration (X_f). The settling flux is smoothly reduced through the Ω function from a height somewhat below the inlet layer downward and reaches zero at the bottom. The inconsistency at the bottom layer is overcome by having a settling flux tending towards zero near the bottom. Therefore, the settling flux equation can be reformulated as:

$$J_{S,i} = \Omega(y, SVI, h_0, X_f)\min(v_{s,i}X_i, v_{s,i+1}X_{i+1})$$

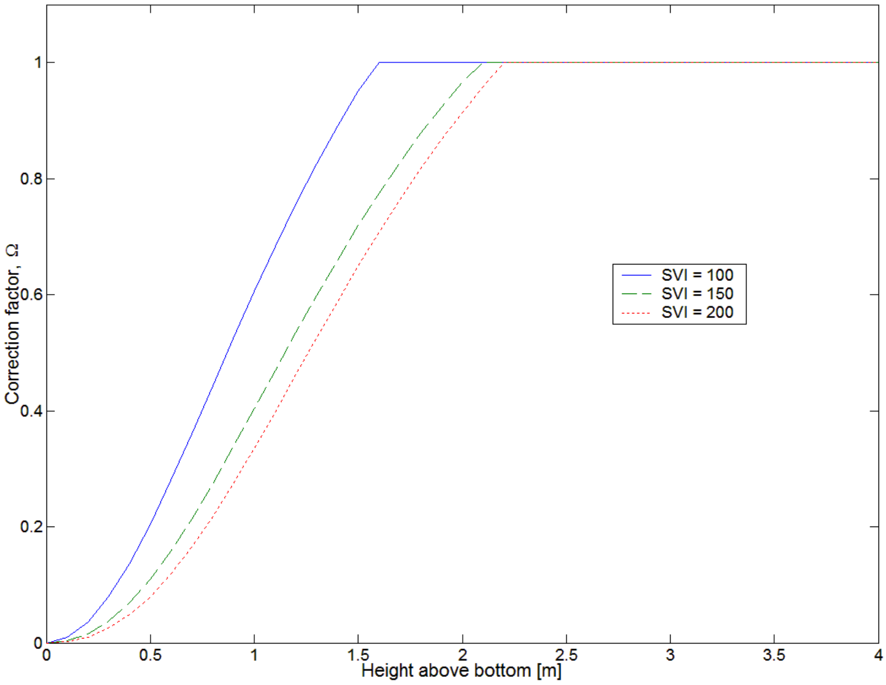

Figure 2: The Härtel–Pöpel correction function for an inlet position at 2.2 m above the bottom at different sludge volume indexes

Model of Dupont and Dahl

The mixed liquor is a flocculent suspension in which larger particles can be formed by the coalescening of particles which have collided. These larger particles generally enhance settling characteristics. The particle distribution is bimodal with primary particles (microflocs) in he 0.5 to 5 µm and flocs (macroflocs) in the10 to 5000 µm range. The settling properties of a sludge depends both on the distribution of primary and floc particles and on how easily the primary particles are entrapped into larger flocs.

Therefore, the components of the influent to the settling tank are divided into three fractions according to the model of Dupont and Dahl: soluble components, non-settleable particulate components (referred as primary particles) and settleable components (macroflocs) [4]. Soluble components and primary particles are considered to follow the hydraulic flow in the settling. The transport of macroflocs in the settling tank is modelled according to the traditional flux theory. The model selected for estimating the amount primary particles was is describing the concentration of primary particles in the influent to the settling tank as a function of the effluent flow rate:

$$X_{\mathrm{PP}} = SS_{\mathrm{Init}} + K_1 \left(\frac{Q_{\mathrm{efl}}}{A} \right)^{K_2}$$

The parameter values in the work of Dupont and Dahl are 3 mg/l, 1.6 and 3 for SS_{Init}, K_1 and K_2, respectively. Consequently, the concentration of macroflocs in the influent to the settling tank is given by:

$$X_{\mathrm{SS}} = X_{\mathrm{SS,I}} - X_{\mathrm{PP}}$$

Settling velocities of the macroflocs for both free and hindered sedimentation were measured and a new model for the settling velocity was proposed. The model was validated with data measured at the wastewater treatment plant Lynetten, Copenhagen, Denmark. The settling velocity has an increasing value for increasing concentrations at low suspended solids concentrations (free settling zone where the mean particle diameter increases with increasing SS concentration) and a decreasing value for increasing concentrations at high suspended solids concentration (hindered settling). The mathematical formulation selected by Dupont and Dahl for the description of the settling velocity is the log normal function of the total concentration of particles (X_{SS} + X_{PP}) in the suspension. It is emphasised that the calculation of the settling velocity depends on the total concentration, while the settling velocity refers only to the macroflocs (X_{PP}) of the suspension.

$$v_s = v_0 \exp\left(-0.5\left(\frac{\ln\left(\frac{X_{\mathrm{SS}} + X_{\mathrm{PP}}}{n_1}\right)}{n_2}\right)^2\right)$$

The suggested model parameters are 8.9024 m/h, 630 m^3/g and 1.065 for v_o, n_1 and n_2, respectively.

A model for the phenomenon of *short-circuiting* is also proposed in the work of Dupont and Dahl. Differences in the density of the influent and the density of the suspension in the settling tank will induce density currents in the tank. In the inlet zone the density current will cause a vertical transport of the influent through the settling tank. Together with the vertical flow caused by the return sludge removal, a substantial part of the influent is transported to the return sludge pit without taking part in the actual settling process. Hereby the suspension withdrawn from the bottom of the settling tanks is diluted to give the actual suspended solids concentration in the return sludge. The proposed model divides the whole influent into two parts: one part makes up the actual influent to the settling part of the settling tank model; the other part of the influent makes up the short-circuiting flow which bypasses the settling part of the settling tank model.

The Otterpohl and Freund model

Otterpohl and Freund also proposed a three components model in their work which can describe the behaviour of the secondary settler under dry and wet weather flows [9]. In their work experiments were made at three municipal wastewater treatment plant operating with different sludge ages. Activated sludge drawn from the effluent of the aeration tank was settled in 1 litre cylinders. The supernatant was analysed for its solids content both by turbidity measurement and filtration at different dilution rates. The results of measurements for small solids components (microflocs) relative to the solids concentration in the aeration tank is given in the following function:

$$f_l = f_0 e^{-aX}$$

where f_l is the fraction of small solids in the aeration tank, f_0 and a are parameters (0.04 and 0.78, respectively). According to their observations, the settling speed of small sludge flocs is constant and

$$v_{\mathrm{s,microflocs}} = 0.01 \text{ m/h}$$

This proved not to be a sensitive parameter until the effluent flow becomes very small. For the estimation of the settling velocity of the macroflocs, the results of Härtel were used. The settling velocity function for macroflocs:

$$v_{\mathrm{s,macroflocs}} = (17.4e^{-0.00581SVI} + 3{,}931)\left(e^{-\left(-0.9834e^{-0.00581SVI} + 1.043\right)X}\right)$$

Furthermore, the settling flux is multiplied with the Ω correction function of Härtel. Therefore, the resulting settling flux can be formulated as:

$$J_{S,i} = \Omega(y, SVI, h_0, X_f)\min(v_{s,i}X_i, v_{s,i+1}X_{i+1})$$

in the thickening zone.

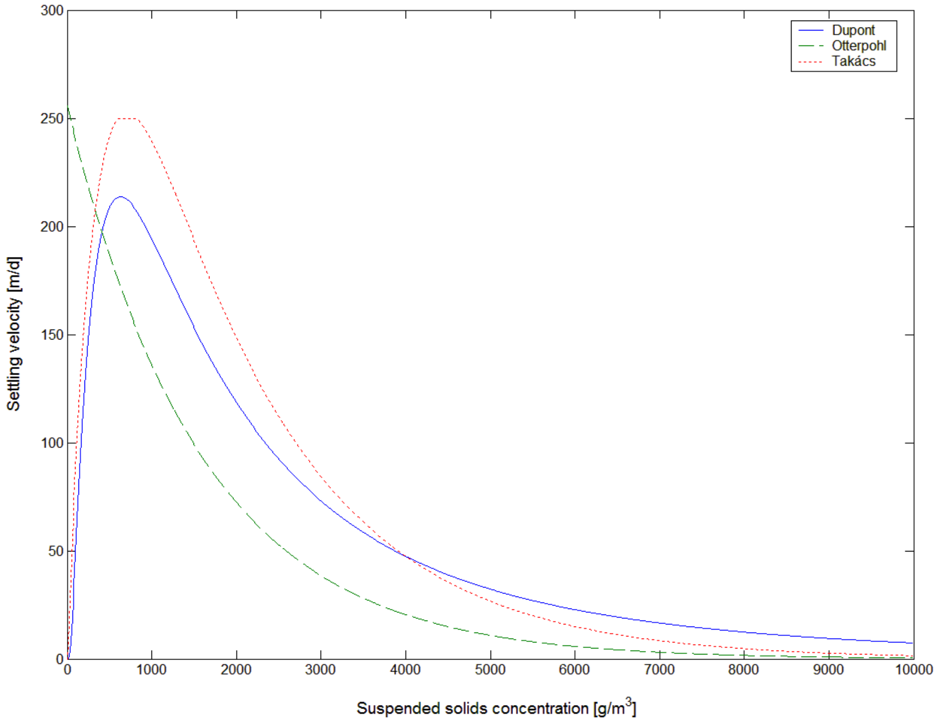

Figure 3: Settling velocity vs SS concentration

Model of Hamilton

To treat the phenomenon of propagating shock wave a conceptual hydrodynamic approach was used by Hamilton *et al.* [5] and other authors [15,16]. An additional eddy diffusion term was added, therefore, the conservation equation can be rewritten as:

$$-\frac{\partial X}{\partial t} = V\frac{\partial X}{\partial y} + \frac{\partial VsX}{\partial y} - D\frac{\partial^2 X}{\partial y^2}$$

where D is the pseudo-diffusivity coefficient. Owing to the diffusion term, the gradient of a shock wave front is decreased while the propagation and the numerical procedure become stable. Nevertheless, it has to be emphasised that D is pseudo-diffusivity coefficient which not only describes the real physical diffusion process, but incorporates turbulent diffusivity, 2-D and 3-D dispersion, errors introduced by numerical methods and the sludge removal process. The introduction of a diffusion term also changes the partial differential equation from convective to convective-diffusive, which makes the final solution become independent of the initial conditions. The model is constructed in the same way as the other models: the mass balance equation is discretized by dividing the settler into a number of layers. In this case, the mass balance for layer i in the thickening zone ($m < i < n$):

$$\frac{\partial X_i}{\partial t} = \frac{J_{dn,i-1} - J_{dn,i} + J_{s,i-1} - J_{s,i} + D(X_{i+1} - X_i)/z_i - D(X_i - X_{i-1})/z_i}{z_i}$$

The suggested model parameter for D is 0.54 $\mathrm{m^2/h}$ by Hamilton.

Reactive one-dimensional models

All the aforementioned models used the assumption that biological reactions are negligible within the secondary settling tank, only the physical reactions were considered. However, in some cases investigation of the biological reactions can be necessary because high denitrification rate can lead to the appearance of nitrogen bubbles and therefore, to the rising of the sludge [12]. Modelling the biological reactions as well as the physical processes in the SST, each layer has to be considered as a continuously stirred tank reactor where biological reactions take place, soluble components are carried by the hydraulic movement and SS are carried by sedimentation and bulk movement. Propagation of the soluble components can be described by the following equation in the thickening zone:

$$\frac{\mathrm{d}S_i}{\mathrm{d}t} = \frac{v_{dn}(S_{i-1} - S_i)}{z_i} \quad \text{where} \quad v_{dn} = \frac{Q_e}{A}$$

For the description of the biological processes traditional activated sludge models can be used like ASM1, ASM2, ASM2d, ASM3. In our contribution the ASM1 model [7] is applied for modelling the biological processes while the physical settling process is still described by the Takács model.

Simulation benchmark

For the purpose of comparison of the different secondary settling tank models, the Simulation Benchmark has been used. The COST 682 Working Group No.2 has developed a benchmark for evaluating by simulation, control strategies for activated sludge plants [3]. The benchmark is a simulation environment defining a plant layout, a simulation model, influent loads, test procedures and evaluation criteria. For each of these items, compromises were pursued to combine plainness with realism and accepted standards. Once the user has validated the simulation code, any control strategy can be applied and the performance can be evaluated according to certain criteria. The layout is relatively simple: it combines nitrification with pre-denitrification, which is most commonly used for nitrogen removal. The benchmark plant is composed of a five-compartment reactor with an anoxic zone and a secondary settler.

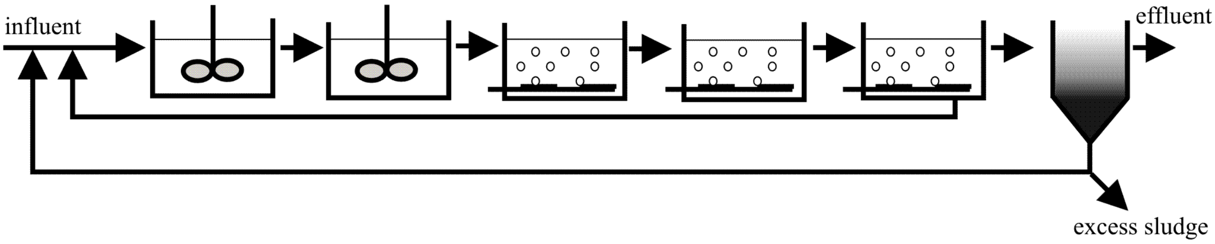

Figure 4: Wastewater treatment plant setup

The plant layout can be seen in Figure 4. The first two compartments makes up the anoxic zone with individual volume of 1000 m^3, and 3 compartments create the aerobic zone with individual volume of 1333 m^3. The oxygen mass transfer coefficient rate (K_La) is set to 240 d^{-1}, while the K_La in the last compartment is 80 d^{-1}. The flowrate of the internal re-circulation is kept at 55338 m^3/d. The secondary settler has a conical shape with the surface of 1500 m^2 and the depth of 4 m. The flowrate of the sludge re-circulation is 18446 m^3/d and the excess sludge is removed from the settler at 385 m^3/d.

Since influent quality and flow rate disturbances play an important role in the operation of wastewater treatment plant, influent disturbances are defined for different weather conditions. In this paper, both dry weather data and wet weather conditions are considered containing 2 weeks of influent data at 15 minutes sampling interval. Parameters for the second week influent are depicted in Figure 5. Diurnal variations and weekly trends (lower peaks in weekend data) are also depicted by these data.

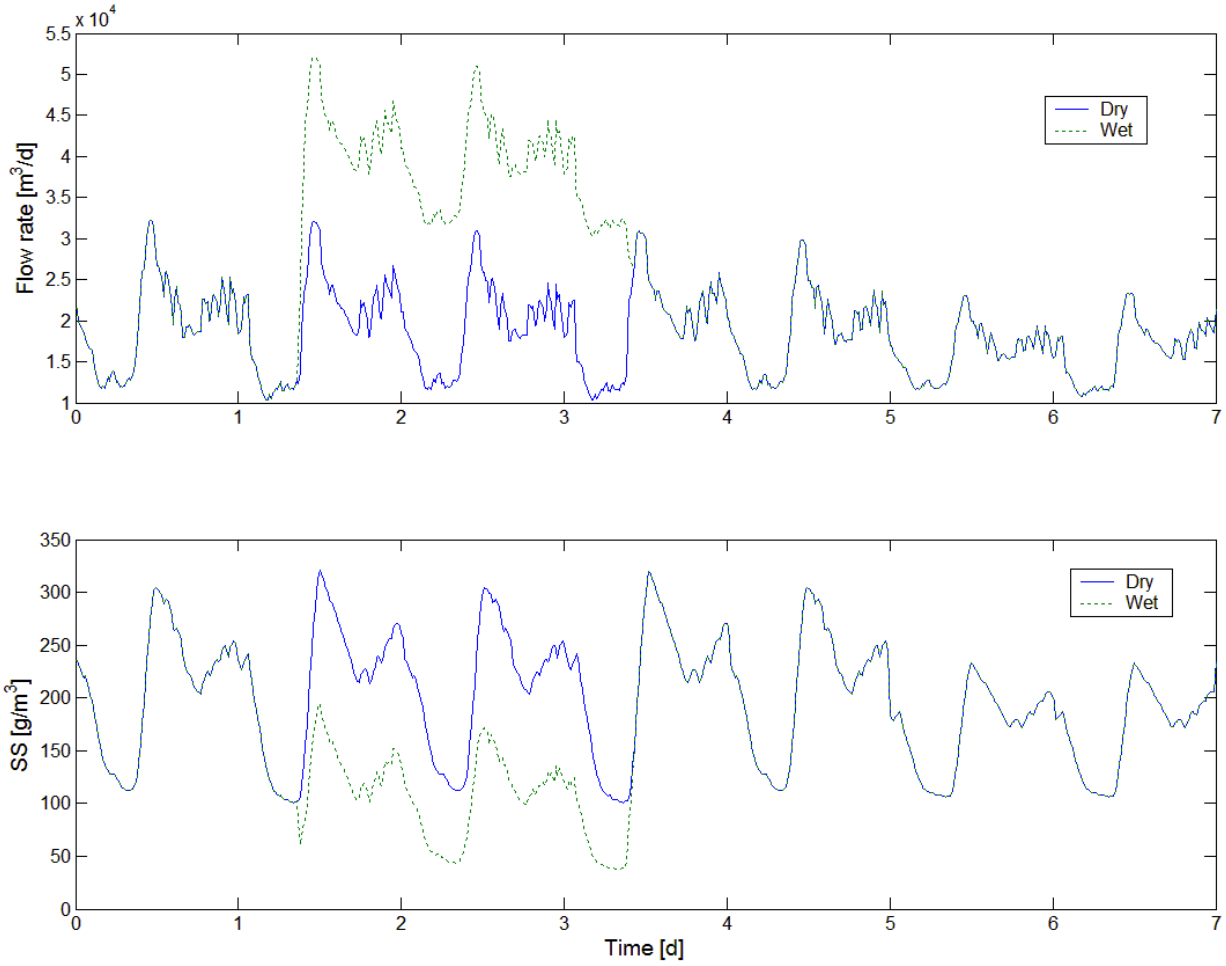

Figure 5: Influent flow characteristics under dry and wet weather

Simulation results

Simulations were carried out using the framework of the Simulation Benchmark but substituting the secondary settler model with the currently investigated model. Both dry and wet weather dynamic simulations were examined. The SST was divided into 10 vertical layers in all cases as described in the Benchmark. Finally six models were compared: the originally described Takács-model; combination of the Takács-model with the Härtel–Pöpel correction function (applied earlier also by [4]); the three fraction models of Otterpohl and Dupont, however, the short-circuiting model was omitted from the Dupont model for better evaluation; the Hamilton-model and a reactive model.

Steady-state results

Investigating a secondary settler model, the initial step is to examine the steady-state SS profile in the secondary settler which can be the starting point for other dynamic simulations.

Since, steady-state solvers often fail to find a steady-state solutions, the steady-state is achieved by using a constant influent until the system reaches the steady-state. It was found that 100–200 days simulation is enough and the final values can be accepted as steady-state values.

The resulting steady-state profiles can be seen Figure 6. The effluent SS concentrations are usually between 10 and 30 g/m^3 (Figure 6) according to the 12.5 g/m^3 of the Simulation Benchmark which applies the Takács-model. The lowest concentration is predicted by the Otterpohl & Freund model (9.77 g/m^3) which is unambiguously due to the settling velocity model estimating very high settling velocity at low SS concentrations (see Figure 6). The highest effluent SS concentration (31.0 g/m^3) is predicted by the Dupont & Dahl model because of the low settling velocity at very low SS concentration. It can been from Figure 6 that that the inlet layer (1.6–2.0 m depth) is dominated by the influent concentration, its concentration moves between 340–360 g/m^3 for all models except the Otterpohl model which predicts lower concentration due to very high settling velocity in the 0–500 g/m^3 SS concentration range. The underflow SS concentrations ranges between 5700 and 6400 g/m^3 according to settling velocity in the thickening zone, however, the distribution of the sludge in the thickening zone shows significant difference: the Härtel, Hamilton and Otterpohl model gives a smooth distribution, the sludge concentration gradually increases with depth. On the other hand, the Takács settling function, the Dupont and the reactive model results in a considerably uniform sludge distribution (350–360 g/m^3) in the thickening zone.

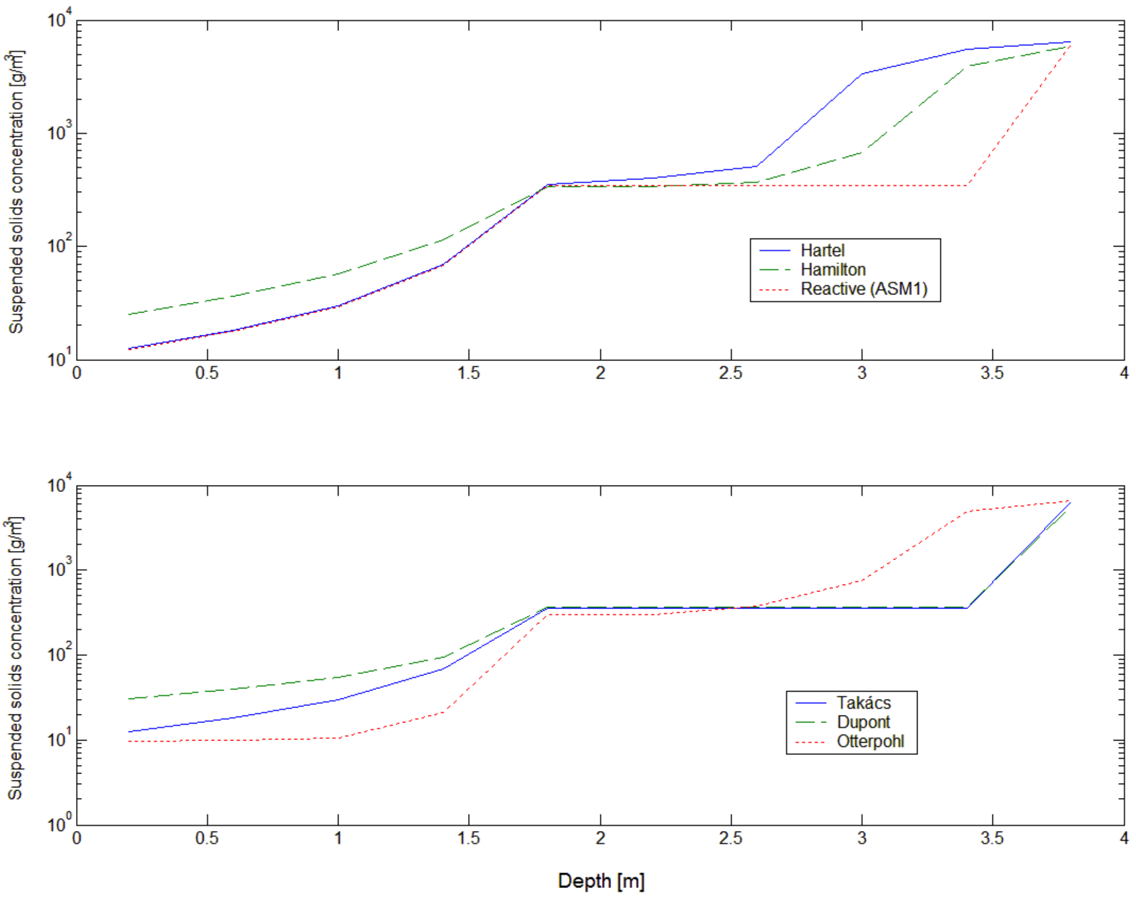

Figure 6: Sludge distribution in the secondary settling tank under steady-state conditions

Dynamic simulations

After having found the steady-state solution, dynamic simulations can be carried out using the influent data depicting the variations in the influent flow and load. Starting from the steady-state the dry weather influent data are used for a 14-day simulation. From the states achieved, further 14 days are simulated using the dry weather and rain event influent data. That is, for any system at steady-state a 28-day dynamic simulation is performed, from which the data of the last seven days are used for process evaluation.

The predicted effluent SS concentrations can be seen in Figure 7. The daily and weekly load variation can be well observed from the results: the diurnal daily deviation and the low weekend flow determine the effluent quality. As expected from the steady-state results, the Dupont and the Hamilton models estimate the highest effluent SS concentrations and the highest daily variation. The second two plots depict the effect of a rain event on the effluent. According to the Dupont model, the SS in the effluent may reach up to 50 g/m^3 during the rain, while the lowest predicted concentration (Otterpohl model) remains below 15 g/m^3.

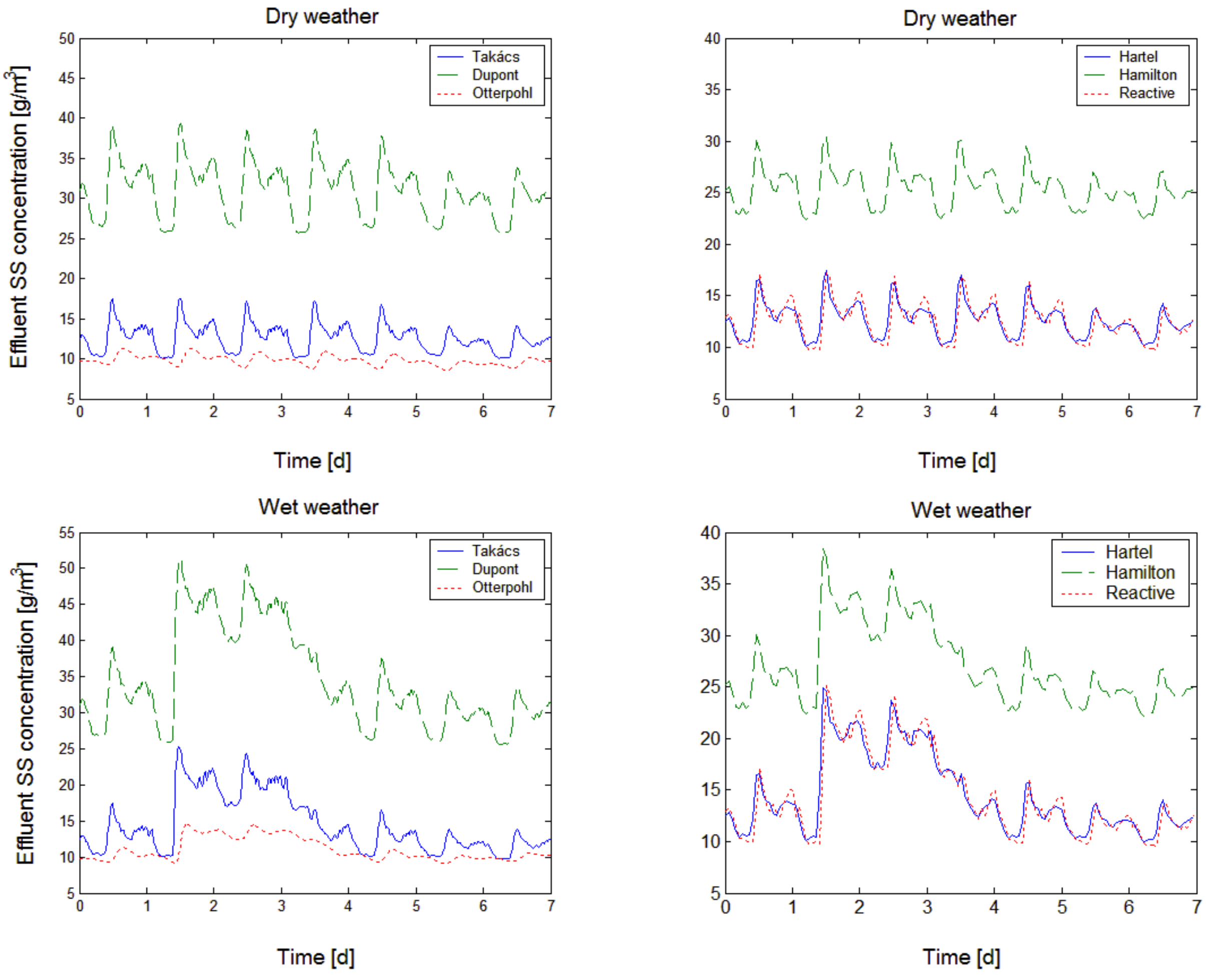

Figure 7: Effluent SS concentration under dry and wet weather conditions

The underflow SS concentrations were also investigated during the simulation, since these are also important parameters as the recycled sludge is used to maintain the SS in the biological reactors, furthermore, the cost for the sludge disposal can be estimated knowing the wasted sludge quantity. The resulting underflow sludge concentration is mainly influenced by the settling velocity value at high sludge concentration in the thickening zone. The highest concentration is predicted by the Otterpohl model which estimated the lowest effluent SS concentration. This is due to the characteristic of the exponential settling velocity model: very high settling velocity in the clarification zone and very low settling velocity in the compression zone. The lowest concentrations are predicted by the Dupont and the Hamilton models.

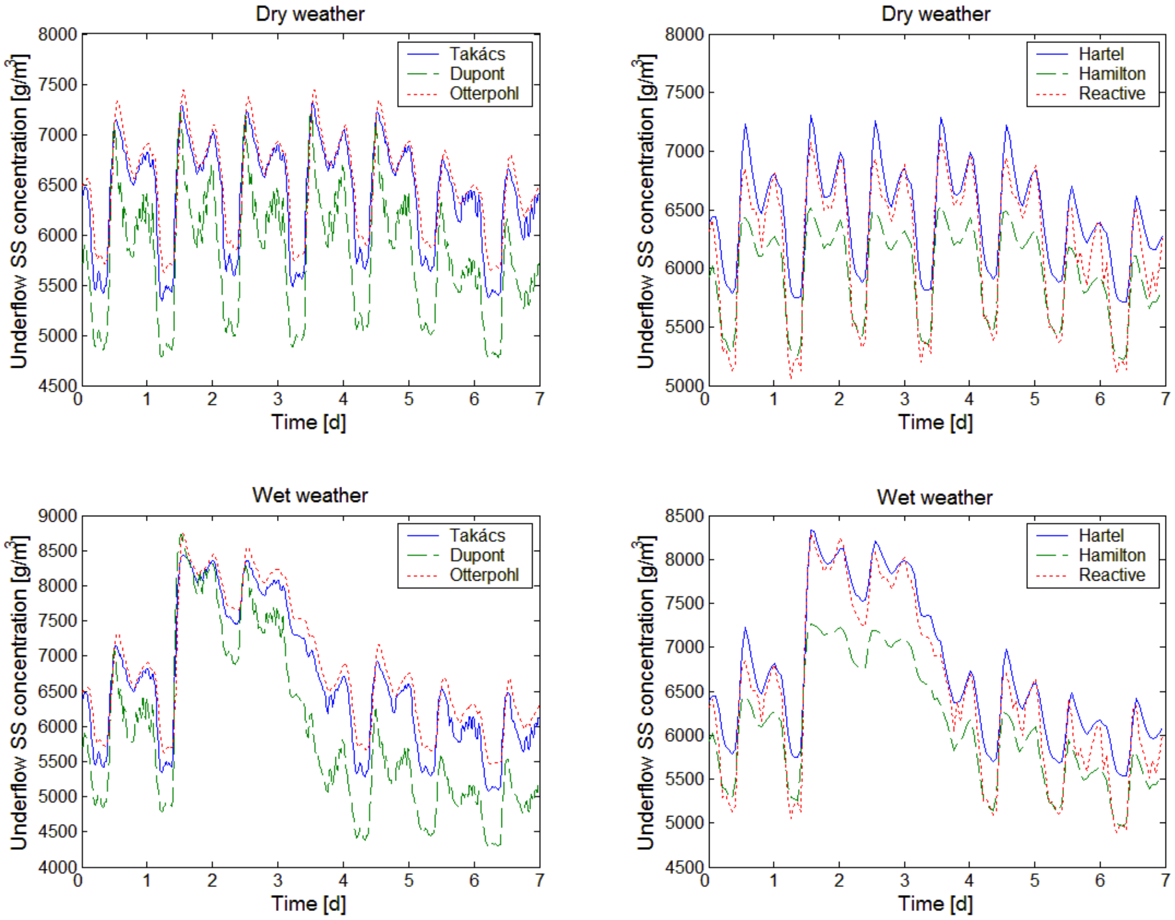

Figure 8: Underflow SS concentration under dry and wet weather conditions

The change in the sludge concentration profile during a 7-day dynamic simulation can be seen in Figure 9. The first figure depicts the profile change during a dry weather scenario and on the second figure a significant rainfall results in the SS concentration increase in the thickening zone of the SST.

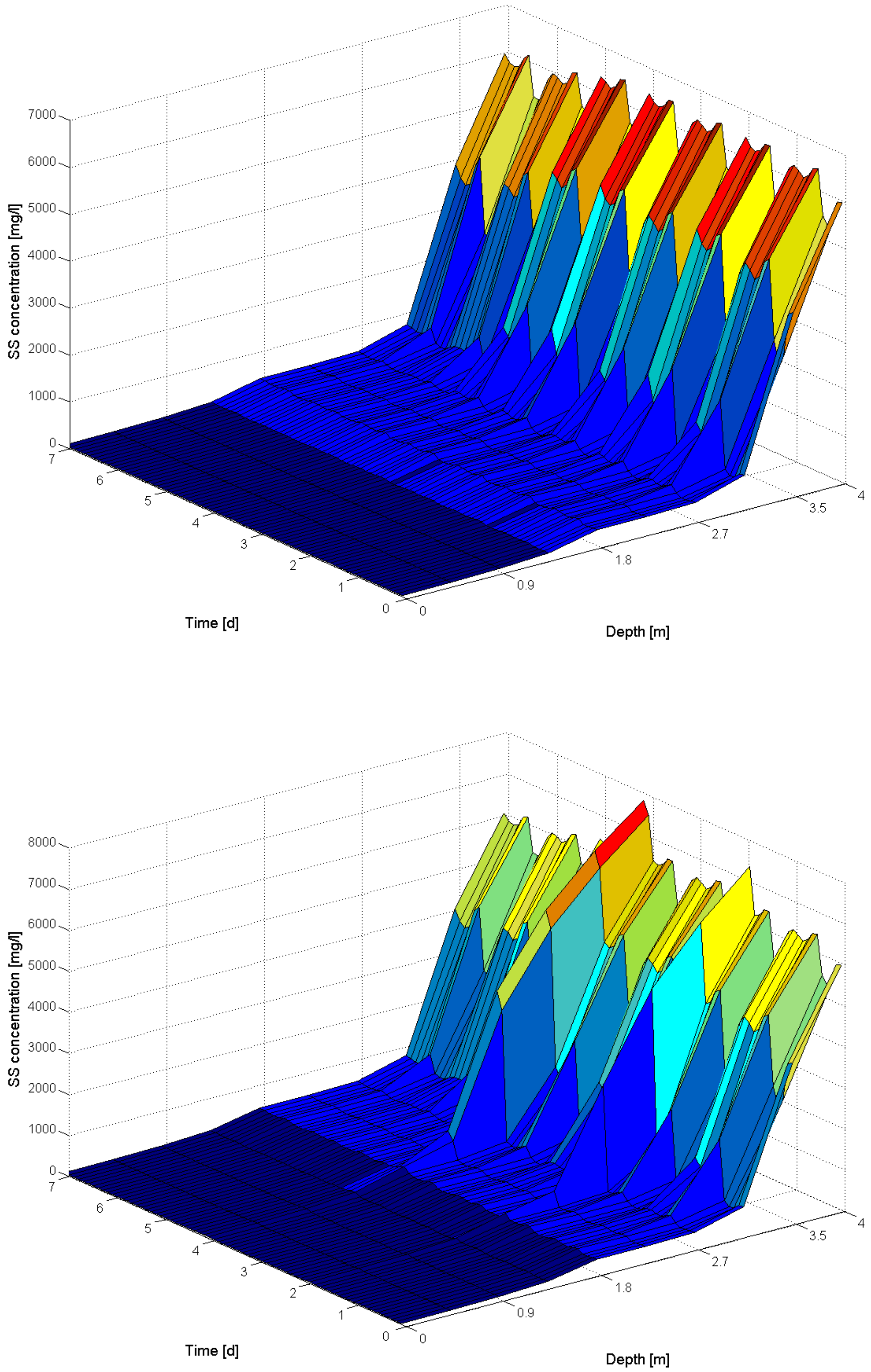

Figure 9: SS profile in the SST during dry and wet weather simulations

Conclusion

The application of one-dimensional models coupled with the activated sludge models gives a reasonable approximation of the sludge balance and of the sludge shift from the aeration tank to the SST where it is partly stored during wet weather loading. Furthermore, application of these models does not require much computation capacity. However, in real plants there exists several phenomena that cannot be reflected in 1-D models like the geometry of the SST (e.g. inlet and outlet arrangement), flow (e.g. short-circuits from the inlet to the outlet; resuspension of the settled sludge blanket) and the sludge removal process (the sludge at the bottom of the tank is diluted). Nevertheless, one-dimensional models are widely used and accepted in computer simulation of wastewater treatment plants nowadays.

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