Impact on sludge inventory and control strategies using the Benchmark Simulation Model No. 1 with the Bürger-Diehl settler model

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Abstract
An improved 1-D model for the secondary clarifier, i.e. the Bürger-Diehl model, was recently presented. The decisive difference to traditional layer models is that every detail of the implementation is in accordance with the existing theory of partial differential equations. The Bürger-Diehl model allows accounting for hindered and compressive settling as well as inlet dispersion. In this contribution, the impact on settler underflow concentration predictions, plant sludge inventory and mixed liquor suspended solids based control actions are investigated by using the Benchmark Simulation Model No. 1. The numerical results show that the Bürger-Diehl model allows for more realistic predictions of the underflow sludge concentration which is essential for more accurate wet-weather modelling and sludge waste predictions. The choice of secondary settler model clearly has a profound impact on the operation and control of the entire treatment plant and it is recommended to use the Bürger-Diehl model as of now in any wastewater treatment plant modelling effort.

Keywords: Clarifier; Compression settling; Layer model; Wet-weather; Underflow

INTRODUCTION

The operation and control of secondary settling tanks (SSTs) is still an important performance-limiting factor in conventional wastewater treatment plants (WWTP). Indeed, the performance of SSTs significantly affects the effluent quality as well as the biomass inventory in the entire plant (i.e. the biomass in the bioreactor and clarifier). As biomass is the driving force for the biokinetic conversion processes, SST operation will affect the performance of the entire treatment plant – in reality and when modelling WWTPs.

Traditional layer models used to date for SSTs and available in most commercial simulation platforms, e.g. the one by Takács et al. (1991), do not capture the settling dynamics in sufficient detail (Li and Stenstrom, 2014b). In Takács' method the governing partial differential equation (PDE) is approximated by a 10-layer simulation. Under normal dry-weather operating conditions, this model may behave reasonably. However, its predictions under situations that diverge from normal operating conditions (e.g. peak flows due to rain events) lose realism. Hence, when simulating WWTPs in these conditions, this settler model could lead to erroneous results.

Several shortcomings that cause this lack of predictive power have been reported (Jeppsson and Diehl, 1996; Plósz et al., 2011; Bürger et al., 2011; Bürger et al., 2012; Li and Stenstrom, 2014a). First, the numerical flux between two adjacent layers has to be chosen in accordance with the PDE theory for this type of conservation equations. Jeppsson and Diehl (1996) investigated the ability of the numerical solution to approximate the analytical solution of the PDE and found that the numerical solutions of Takács' model do not converge to the solution of the PDE when the number of layers is increased. Moreover, the numerical settling flux function in the Takács model contains an empirical constant X_T in the numerical algorithm which is not present in the governing PDE. This is in conflict with one of the fundamental principles for any consistent modelling methodology (Bürger et al., 2011) which states that each model parameter should be present in the governing equations and no parameter should be introduced in the numerical method itself. Jeppsson and Diehl (1996) proposed the Godunov scheme as an alternative method. This scheme has since then been used in a number of studies (Diehl and Jeppsson, 1998; Plósz et al., 2007; Bürger et al., 2013) and has been proven to be mathematically sound (Bürger et al., 2011). Another numerical flux connected to PDE theory has recently been introduced for SST simulation by Li and Stenstrom (2014a).

A second important shortcoming of both the traditional layers models, e.g. the one by Takács et al. (1991), and the recent one by Li and Stenstrom (2014a) is that they only account for convective flow and gravity settling. Other phenomena occurring in an SST such as compression settling, turbulent diffusivity and dispersion are not included. Takács' model compensates for these missing effects by applying a coarse discretisation (10 layers) which introduces significant numerical dispersion making the numerical solution more representative of typically observed sludge concentration profiles. Although this artificial smoothening imposes a more realistic profile, it is not able to describe the true dynamics of an SST causing modellers to perform unrealistic calibrations of the settling parameters or even changing the number of layers not realizing that this impacts the numerical dispersion. It should be mentioned that attempts have been made to handle this shortcoming of Takács' model by accounting for compression through the inclusion of additional terms in the settling flux function (Stricker et al., 2007). This means that the governing PDE still has only first-order derivative terms. It is, however, commonly known that compression necessarily involves also the gradient of the concentration leading to second-order smoothing terms in the PDE.

More recently developed 1-D models attempt to explicitly account for dispersion and compression effects by incorporating a second-order term in the governing PDE (Hamilton et al., 1992; Watts et al., 1996; Lee et al. 2006; Plósz et al., 2007). By introducing a second-order term Plósz et al. (2007) showed that dispersion can be modelled as a separate phenomenon and not by numerical dispersion introduced through the discretisation. Moreover, by using the Godunov flux the numerical solutions will converge to the analytical solution of the PDE allowing the user to apply a finer discretisation grid and thus resulting in improved predictions of the SST behaviour. The drawback of this approach is, however, that all the previously unmodelled phenomena (such as compression settling and inlet dispersion) are now lumped into one single term. This is too coarse to sufficiently capture the true settling dynamics, creating the risk of compensating uncaptured dynamics by either unrealistic calibration of the settling parameters or by introducing an extra parameter in the numerical solution (for example the reduction factor η_c in the model by Plósz et al. (2007) which is not present in the original governing PDE). As mentioned above, such a procedure is not consistent with good modelling practice.

A new 1-D model which allows improved and more realistic simulations of secondary clarifiers has recently been presented (Bürger et al., 2011; Bürger et al., 2012). All implementation details can be found in Bürger et al. (2013). This new model, called the Bürger-Diehl model, is based on the correct numerical solution of its governing PDE by appropriate methods. Furthermore, it allows the modeller to account for several phenomena in a modular way making it very flexible in its application.

The specific objective of this study is to investigate the effect the Bürger-Diehl model has on operation and control of a WWTP. For this purpose simulations are performed with the COST/IWA Benchmark Simulation Model No.1 (BSM1) (Copp, 2002; Gernaey et al., 2014). Moreover, we elucidate the specific added value of the settler model's features on the predictions of biomass concentrations throughout the system and the development of mixed liquor suspended solids (MLSS) based control actions. Finally, some guidelines with respect to the application of this new settler model in WWTP modelling in general are also provided. The results obtained with the Bürger-Diehl model are here compared to the Takács model since this is historically the most commonly used one in the WWTP community.

MATERIALS AND METHODS

Benchmark Simulation Model No.1

The COST/IWA Benchmark Simulation Model No.1 (BSM1) (Copp, 2002; Gernaey et al., 2014) is a standardised simulation procedure for the design and evaluation of control strategies of conventional WWTPs in terms of effluent quality and operational costs, comprising a detailed description of plant layout, models, inputs and evaluation criteria; see Figure 1.

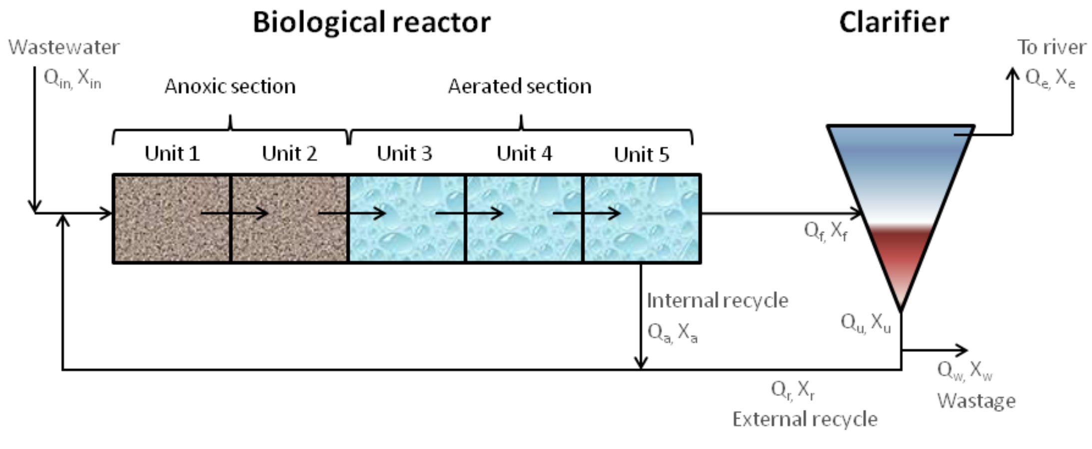

Figure 1: General overview of the BSM1 plant.

The results shown in this contribution were obtained with the BSM1 with two different settler models (Bürger-Diehl and Takács) in the modelling and simulation platform WEST (http://www.mikebydhi.com, Denmark; Vanhooren et al., 2003). All simulations were performed under storm-weather conditions in order to highlight the impact of the settler model. The input flow rate (Q_{in}) as well as the incoming concentrations of readily biodegradable substrate (S_S) and ammonium (S_{NH}) are shown in Figure 2.

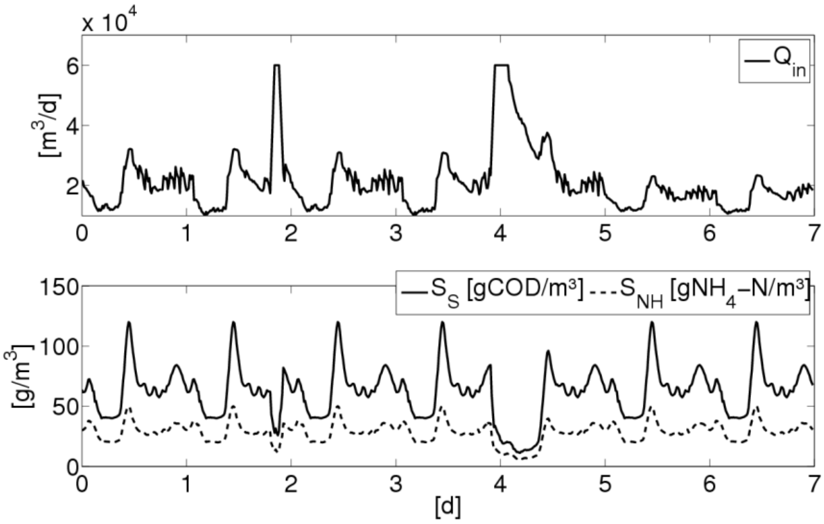

Figure 2: Three inputs of the BSM 1 model under storm–weather conditions

Bürger-Diehl settler model

The Bürger-Diehl model is based on the following spatially 1-D PDE for the biomass concentration X at time t and depth z from the feed level:

$$\frac{\partial X}{\partial t} = -\frac{\partial}{\partial z}F(X,z,t) + \frac{\partial}{\partial z}\left(\{\, d_{\mathrm{comp}}(X) + d_{\mathrm{disp}}(z, Q_{\mathrm{f}}(t))\}\frac{\partial X}{\partial z}\right) + \frac{Q_{\mathrm{f}}(t)C_{\mathrm{f}}(t)}{A}\delta(t)$$

The first term on the right-hand side represents convective transport (due to feed flow, underflow and overflow) as well as particle transport due to gravity settling. The second term on the right-hand side includes a compression function (d_{comp}) and a dispersion function (d_{disp}) which can be switched on or off by the user depending on the model study requirements. The last term on the right-hand side is a singular (only occurs in 1 layer, i.e. the feed layer) source term modelling the feed mechanism (Q_{f} is volumetric inflow rate to the settler, A is the constant cross-sectional area).

To numerically solve this PDE, it is discretised by dividing the tank into a user-defined number of layers (N). The flux $F(X,z,t)$ in the PDE is replaced in the simulation algorithm by numerical fluxes containing the Godunov flux. Moreover a specific implementation of the compression term is needed to ensure that as the number of layers increases, the numerical solution becomes more accurate and converges to the physically correct solution of the PDE. In the Bürger-Diehl model, the number of layers N can thus be set by the user depending on the desired accuracy and on the computational time and resources available. Some guidance is provided in the section on practical implications.

In order to calculate the correct effluent and underflow concentrations, two extra layers are added at the top and bottom of the tank, respectively. It is important to emphasize that the effluent and underflow concentrations are generally not the same as the concentrations in the top and bottom layers within the settler (Jeppsson and Diehl, 1996). This is not taken into account in the currently used layer models. The extra layers in the underflow region can be interpreted physically as the start of the outlet pipe. The underflow concentration X_{u} can be defined as the concentration in any of these two layers.

Important features of the Bürger-Diehl model are the optional inclusion of compressive settling (becoming active above a certain critical gel concentration, X_{crit}) and flow-rate-dependent inlet mixing phenomena. This is achieved by specific terms for compression and dispersion in the 1-D PDE. The model is very flexible since the compression and dispersion terms can be switched on or off to meet the user's needs. Hence, in its simplest form (no compression and no inlet dispersion), the Bürger-Diehl model reduces to the one presented by Diehl and Jeppsson (1998) and is a reliable alternative for current models. If needed in the modelling study, compression and inlet dispersion can easily be added while the model still produces correct solutions.

The flux *F(X,z,t)* in the PDE contains the hindered settling velocity which can be modelled by the settling velocity function of Takács (other expressions do exist and can be used in conjunction with the Bürger-Diehl model as well)

$$v_{\mathrm{hs}}(X) = V_0(\mathrm{e}^{-r_{\mathrm{h}}X} - \mathrm{e}^{-r_{\mathrm{p}}X})$$

with V_0, r_{h} and r_{p} as settling parameters.

The compression function is based on the work of De Clercq et al. (2005) who performed in-depth batch experiments and measured detailed concentration profiles by use of a radiotracer. From these concentration profiles the following relation between concentration and sediment compressibility was derived through inverse modelling (De Clercq et al., 2008):

$$d_{\mathrm{comp}}(X) = \begin{cases} 0 & \text{if } 0 \leq X < X_{\mathrm{crit}} \\ \dfrac{\rho_{\mathrm{s}} \,.\, \alpha \,.\, v_{\mathrm{hs}}(X)}{g(\rho_{\mathrm{s}} - \rho_{\mathrm{f}}).\,(\beta + X - X_{\mathrm{crit}})} & \text{if } X \geq X_{\mathrm{crit}} \end{cases}$$

Here ρ_{s} and ρ_{f} are the densities of the solids and the fluid, respectively, g is the constant of gravity, v_{hs} the hindered settling velocity and α and β are two compression parameters. The compression term is active wherever the concentration exceeds a critical concentration (X_{crit}), which is another model parameter.

One drawback of this function is that there are three parameters (α, β and X_{crit}) to be determined. In combination with the parameters in the settling velocity function this amounts to a total of six parameters that need calibration. It is known that the overall calibration problem is an ill-posed problem (Diehl, 2014). It is therefore of interest to reduce the number of parameters to be estimated. Another problem with the function of De Clercq et al. (2008) is that it does not have an exact primitive which complicates the implementation. Therefore the following constitutive function having only two parameters (γ and X_{crit}) was used in this study:

$$d_{\mathrm{comp}}(X) = \begin{cases} 0 & \text{if } 0 \leq X < X_{\mathrm{crit}} \\ \dfrac{\rho_{\mathrm{s}} \,.\, \gamma \,.\, v_{\mathrm{hs}}(X)}{g(\rho_{\mathrm{s}} - \rho_{\mathrm{f}})} & \text{if } X \geq X_{\mathrm{crit}} \end{cases}$$

Figure 3 illustrates the correspondence between this simplified function (for X_{crit} = 5 g/l and γ = 1.2 m²/s²) and the function by De Clercq et al. (2008) (for X_{crit} = 5 g/l, α =

5 Pa and β = 4 g/l). It can be observed that this simplified function represents a reasonable approximation of the function by De Clercq et al. (2008). Note that it is not the scope of this work to propose this function as the ultimate approach to model compression but merely to illustrate the added value of extending a settler model with this phenomenon in a modular way. Due to the modular structure of the presented numerical scheme the constitutive function can easily be updated or replaced whenever future research provides further insight in the compression phenomenon.

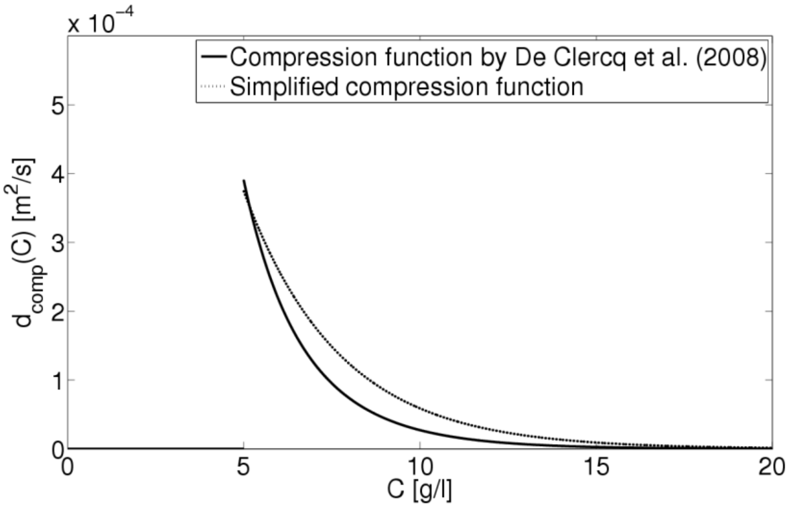

Figure 3: Behaviour of different compression functions in function of sludge concentration

The dispersion function d_{disp} is often set as the product of the fluid velocity and a continuous function of the depth. The continuous function has its maximum at the feed level and is zero some distance away from the inlet (Bürger et al., 2013). This allows modelling a region of higher turbulence around the feed inlet at increased hydraulic loading. The height of the affected region is related to the incoming flow rate. The effluent concentration will thus be influenced by the incoming feed flow and can be calibrated with the dispersion function and not using the degrees of freedom of the settling function as is often artificially done nowadays. Since the goal of this contribution is to investigate the impact of the choice in settler model on the sludge inventory and related control actions, the focus will be on the effect of adding compression settling. The impact of the dispersion function is therefore outside the scope of this paper.

The parameter values used for the different simulations throughout this work are summarised in Table 1.

Table 1: Parameter values for the different constitutive functions used in this study

Parameter	Value
Hindered settling	
V_0 [m/d]	474
r_h [l/g]	0.576
r_p [l/g]	2.86
Compression	
X_{crit} [g/l]	5
γ [m²/s²]	1.2

RESULTS AND DISCUSSION

Impact of compression settling on predicted concentration profiles in the SST

To better understand the importance of including compression settling in an SST model, it is helpful to first consider the behaviour of a full-scale clarifier under both dry- and wet-weather conditions. Therefore, online measurements of both underflow concentration and sludge blanket height (SBH) during a two-day period of dry-weather followed by a two-day storm event at the WWTP of Eindhoven (The Netherlands) are provided in Figure 4. The total height of the tank is 4 m and the feed inlet is located at the top of the tank. The underflow rate in this WWTP is controlled as a fixed ratio (0.65) of the incoming flow rate.

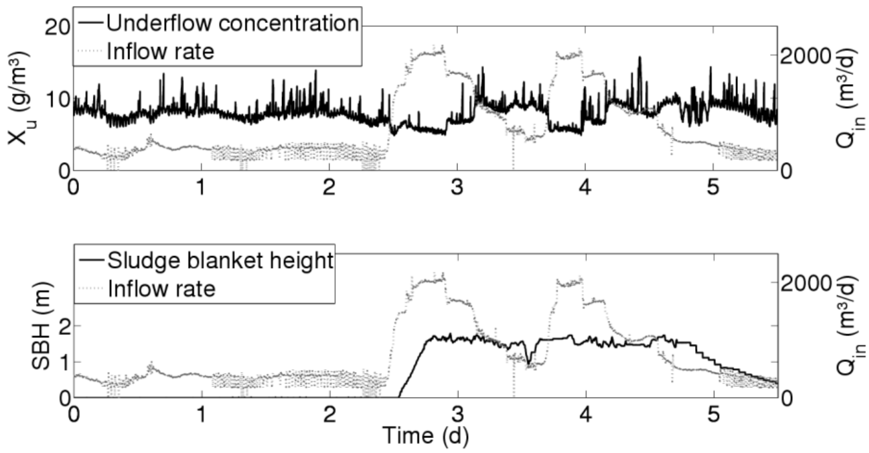

Figure 4: On-line measurement data of underflow concentration and SBH during the period of June 1-6, 2013 at the WWTP of Eindhoven (The Netherlands). SBH is the height from the bottom over which the concentration surpasses 0.9 g/l.

From these data an important distinction can be made between the operational state and consequent control requirements during respectively dry- and wet-weather. During dry-weather, no sludge blanket is detected in the settler signifying that under these conditions the settler is overdesigned and operating at only a fraction of its potential capacity. This is unfortunately the case for many WWTPs worldwide. This indicates that during dry-weather the system's efficiency could be increased significantly for example by operating the bioreactors at a higher sludge concentration. In contrast, when a storm peak hits the WWTP, a sludge blanket of almost 2 meter is formed and care needs to be taken to avoid the loss of sludge from the system. The underflow concentration on the other hand does not undergo any large variations during the storm event. Only a small dilution effect can be observed. Hence, it becomes clear that in this case the main impact of a storm-weather event can be found in the SBH variations.

The SBH can thus be a crucial operation and control variable during a storm-weather event or when imposing higher solids loads to e.g. operate the bioreactors at a higher sludge concentration even during dry-weather conditions (implying higher conversion rates and hence, more flexibility in operation). It is important to develop improved insight (which also implies good quality predictions) in order to judge as of when process control should focus on keeping sludge in the system and safeguarding effluent quality or to maximise conversions.

To illustrate the effect of compression settling on the SST performance, open loop simulations (with a fixed underflow rate Q_u=18831 m³/d) are performed (1) with the model of Takács and (2) with the Bürger-Diehl model with the compression function enabled. Figure 5 shows the differences in SBH and underflow concentration predictions between both models. The sludge blanket height is defined as the height of the first layer with a concentration that exceeds the threshold value of 0.9 g/l. An increased flow rate to the clarifier in the simulations with the Bürger-Diehl model will cause the sludge blanket level to rise significantly and result in only a modest increase in the underflow concentration. This contrasts with a very drastic increase in the underflow concentration and a moderate effect on the SBH in the Takács model. By only considering hindered settling, the sludge in the Takács model will settle unrealistically fast resulting in a highly concentrated bottom layer. By including compression, settling will be slowed down at higher concentrations due to a compressive force. Hence, the inclusion of compression settling creates a dampening effect on the underflow concentration resulting in smaller variations on the underflow but a pronounced increase of the SBH.

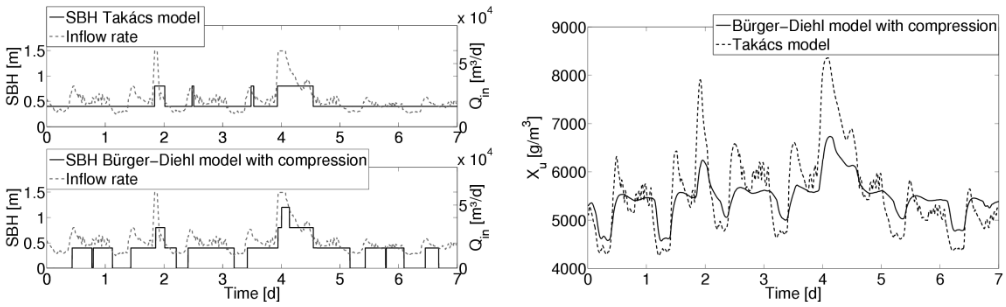

Figure 5: Open loop (Q_u=18831 m³/d) dynamic simulations of the sludge blanket height (left) and underflow concentration (right) for the models of Takács and Bürger-Diehl under storm-weather conditions. Both models were discretised with 10-layers for fair comparison.

To compare the behaviour of the models to the measurements in Figure 4, closed loop simulations were performed where the underflow rate was no longer considered a constant value but as a fixed ratio of the incoming flow rate (as is the case in the WWTP of Eindhoven). As the waste flow rate is kept at a constant value of 385 m³/d, only the recycle flow rate to the biological reactors will vary. The results are shown in Figure 6. In the case of the Takács model, an increased loading to the clarifier during a storm peak results in a significant dilution of the underflow concentration and only a very short elevation of the sludge blanket. On the other hand, the simulations with the Bürger-Diehl model (with compression) yield that variations in the underflow concentration are more moderate and only a slight dilution effect can be observed during the storm peaks. Here, the elevation in sludge blanket is clearly the dominant effect which corresponds to the observations made in reality. It thus becomes clear that by accounting for compressive settling, the SBH and underflow concentrations can be modelled in a more realistic way. Note that we only demonstrate a proof of principle and do not claim a calibrated compression model.

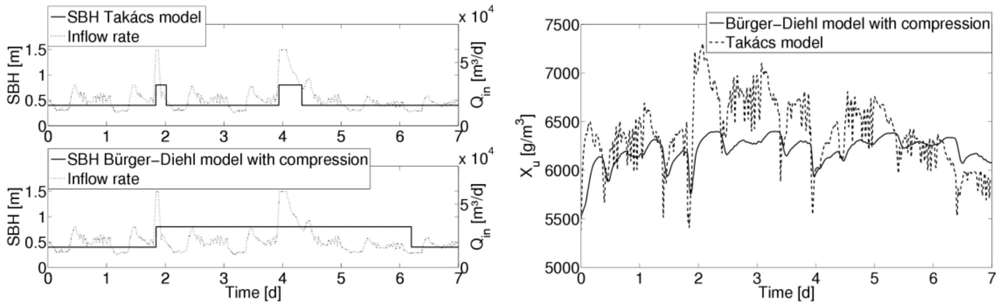

Figure 6: Closed loop (Q_u=0.65*Q_{in}**)** dynamic simulations of the sludge blanket height (left) and underflow concentration (right) for the models of Takács and Bürger-Diehl under storm-weather conditions.

To further illustrate the differences in behaviour between the two settler models, the complete concentration profiles for the open loop simulations at times *t*=0.1 d (before the storm event) and *t*=4.2 d (when the maximum flow rate hits the SST) are shown in Figure 7. From these concentration profiles the importance of another feature of the Bürger-Diehl model becomes evident. The inclusion of additional layers at the outlet boundaries does not only allow more realistic predictions of the underflow concentrations but also influences the entire concentration profile including the SBH.

As could be seen from the simulation results in Figure 5, the SBH in Takács' model never drops below a value of 0.4 m, corresponding to the thickness of the bottom layer. This minimum SBH is inherent to the structure of the Takács' model: sludge settles to the bottom of the tank and accumulates in the last layer. (Adding additional layers to reduce the thickness of the bottom layer is not to be done for the Takács' model as one changes the numerical dispersion and hence the dispersion of the settler.) Unless the settler would be operated at extremely dilute circumstances, Takács' model will never be able to predict a sludge blanket of 0 m. However, when observing the situation in a full-scale treatment plant, the absence of a sludge blanket is often encountered in practice during dry-weather operation. Consequently, the Takács model predicts a persistent error of almost half a meter. The reason for this behaviour is the commonly made but erroneous assumptions that the underflow concentration is always equal to the one in the bottom layer. In the Bürger-Diehl model this problem does not occur due to the existence of additional layers below the bottom which represent the underflow region (modelling the start of the outlet pipe). During dry-weather, the sludge settles without any compression and accumulates in the underflow layers resulting in a predicted SBH of 0 m. When the sludge loading to the clarifier increases, sludge will accumulate also inside the SST and a SBH larger than 0 will be predicted. Thus, by explicitly modelling the underflow region as well as extending the settling behaviour with a compression function, a more advanced 1-D model provides more realistic predictions of the SBH behaviour which would allow operating the SST in a more efficient way.

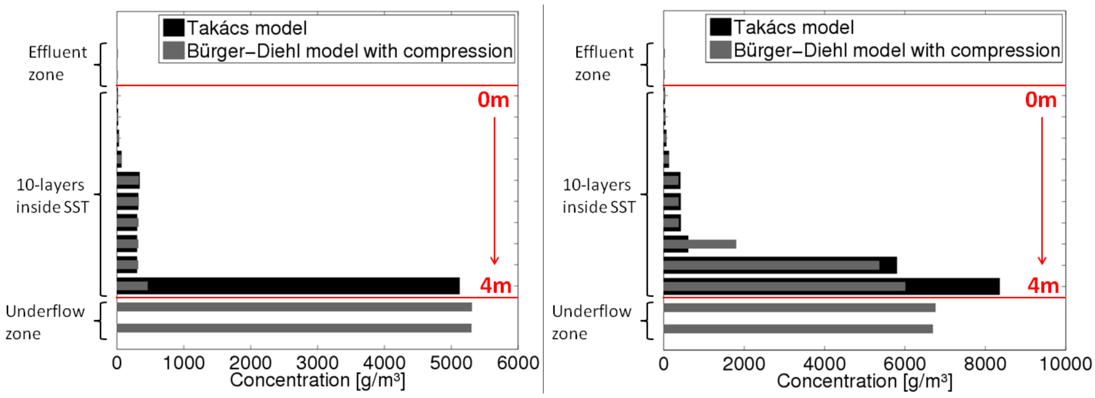

Figure 7: Concentration profiles during dry-weather (*t*=0.1 d - left) and storm-weather (*t*=4.2 d - right) for the two settling models.

Impact of compression settling on the performance of the biological reactors

The previous section illustrates that sediment compressibility notably influences the SBH and the underflow concentration. Whereas the SBH is mainly important with respect to the performance of the SST, the impact range of the underflow concentration stretches out much further as a large part of the underflow is recycled to the bioreactor. Hence, compression settling influences the biosolids concentration in the bioreactors. Figure 8 shows the predictions for the MLSS concentration in the first activated sludge unit (ASU 1) for both the Takács and the Bürger-Diehl model with compression. The latter model increases the predicted effect of a storm peak on the MLSS concentration (i.e. dilution directly after the peak and increased concentration during the recovery phase after a peak event). Due to the dampening effect of compression on the underflow concentration in the Bürger-Diehl model, less sludge is instantaneously returned to the bioreactor when a storm hits compared to the Takács model. This results in less recovery and a more pronounced effect of the storm peak on the bioreactor performance. Thus, traditional settler models, which do not account for compressive settling, might severely underestimate the effect of a storm event due to an underestimation of the biomass dilution effect in the bioreactor and hence instantaneous severely reduced conversion rates. The latter will result in underprediction of potential peaks in the effluent COD and NH_4. When using such a model for developing mitigation strategies under wet-weather, one risks taking insufficient action.

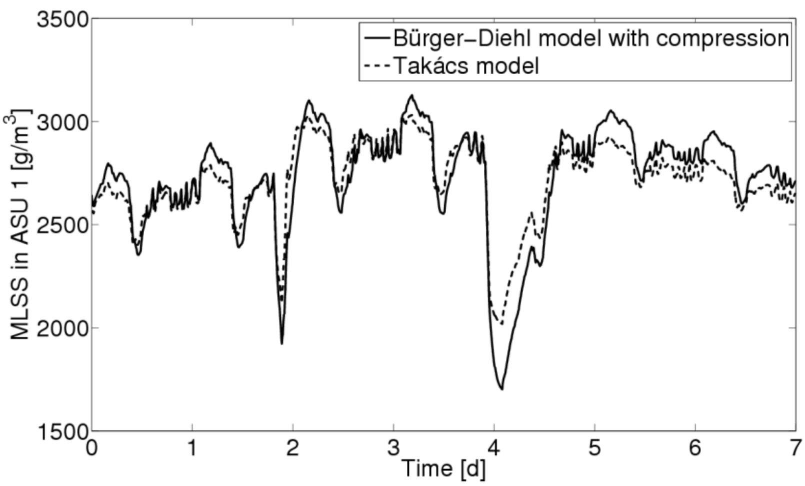

Figure 8: Simulated MLSS concentration in the first activated sludge unit.

Moreover, the MLSS concentration will directly influence the conversion rates in the biological reactors since these are typically of the form $r=\mu X$, where μ is a growth kinetics function. As an example, the nitrification rate in the first aerated activated sludge unit is shown in Figure 9. From this figure it becomes clear that the effect of compression settling will influence the performance of the entire treatment plant. The observed differences in underflow concentration between the models result in a maximal difference of almost 20% for the predicted nitrification rate. Hence, when only hindered settling is considered (as is the case for the currently used layer models), this might "force" modellers to calibrate kinetic parameters for the wrong reasons. If X is wrongly predicted by the model, the degrees of freedom in μ (e.g. μ_{max}, affinities , etc.) will be used to obtain the correct value for the total conversion rate r. Figure 9 further demonstrates that slight differences in conversion rates already exist during dry-weather operation. The relative error also needs some time to reduce to lower values after a storm event.

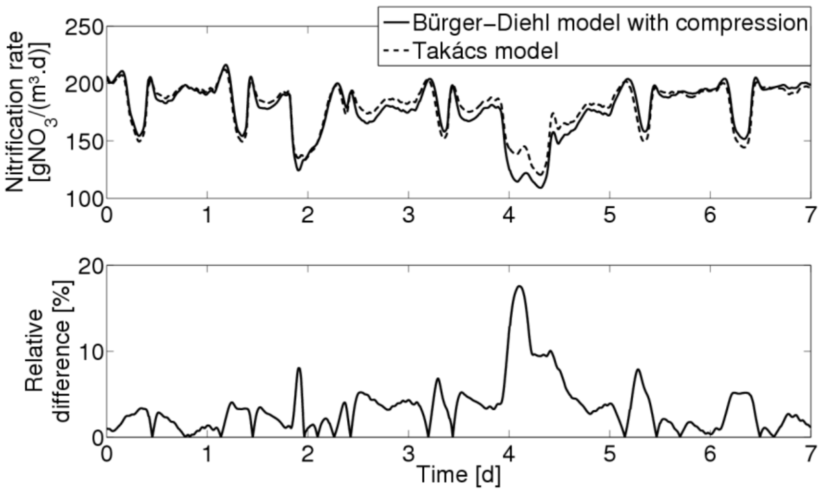

Figure 9: Simulated nitrification rate in the 3rd activated sludge unit (1st aerated unit) during storm-weather conditions.

Impact of compression settling on the development of control strategies

Since the sludge inventory is the driving force behind the performance of a WWTP, a pronounced difference in the predictions of the biomass concentrations will also influence plant-wide control strategies. To investigate the significance of this influence, a control strategy that aims to maintain the MLSS concentration in a desired range was implemented. As a first step, a very simple control strategy was adopted, i.e. controlling the underflow rate as a fixed ratio (0.65) of the incoming flow (note that in the open loop BSM1, a fixed and uncontrolled underflow rate is used). The waste flow is kept at a constant value of 385 m^3/d. This control strategy should reduce the plunge in the MLSS concentration during a storm event since more sludge will be recycled to the biological tanks. However, during highly dilute conditions (which usually occur during storm-weather conditions) this control strategy can become insufficient. Therefore the constant-ratio controller was extended with a PI controller which controls the MLSS concentration in ASU1 at a setpoint of 2800 g/m^3 by adapting the underflow rate (Q_u see Figure 1). The control strategy is implemented in ASU1 since this is the first location where disturbances in the incoming flow will be perceived. If the dilution effect is counteracted here, it will also counteract the effect in the downstream bioreactors. The PI controller serves as an auxiliary control strategy and will therefore only become active if the MLSS concentration drops below

2500 g/m³. Once the MLSS concentration surpasses an upper threshold (MLSS>2850 g/m³), the PI controller is switched off. The limits for manipulation of the underflow rate are set to 0.33 and 1.5 times Q_{in} (Tchobanoglous et al. 2003).

As Takács' settler model is still the most commonly used for WWTP simulations, it was chosen in the BSM1 for the tuning of the PI controller. A suitable system response was found for the controller parameters K_p=10 and τ_I=1. Subsequently, the constant-ratio controller and supplementary PI controller (with K_p=10 and τ_I=1) were implemented for the BSM with the Bürger-Diehl model. The resulting manipulations in underflow rate and predicted MLSS concentrations are shown in Figure 10.

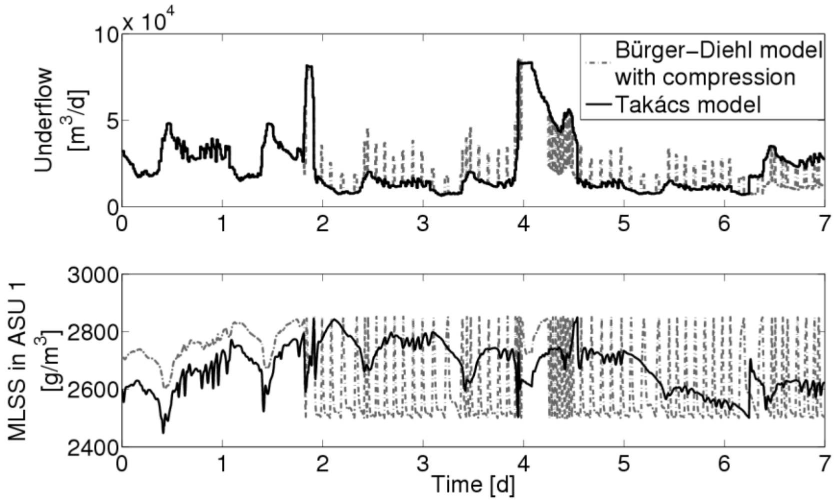

Figure 10: Dynamic simulation with the implementation of an MLSS control strategy (Q_u=0.65*Q_{in} + PI controller with K_p=10 and τ_I=1). Manipulation in underflow rate (top) and MLSS concentration in the first activated sludge tank (bottom) under storm-weather conditions

Prior to the storm event, the control action behaves similar for both models. However, the first storm peak results in significantly deviating control actions on the underflow rate. Whereas the suggested control settings work well in the Takács model for which they were tuned (the controller responds very fast and the dilution of the MLSS concentration due to the storm peak is almost completely reduced), they do not seem to work for the Bürger-Diehl model as can be seen from the very unstable behaviour of the MLSS concentration. These results indicate that when developing control strategies the choice of settler model can have a significant impact. A control strategy developed and tuned with the Takács model does not work for the Bürger-Diehl model, which has been shown to predict a more realistic system behaviour. Consequently, developing such a control strategy based on Takács' model poses a risk of not producing the desired system behaviour under closed loop conditions in practice.

In order to evaluate this risk, it is investigated which aspects of the model structure cause the observed differences in Figure 10. The abrupt fluctuations in the MLSS concentration for the Bürger-Diehl model are caused by the PI controller which is frequently switched on and off. Two phenomena can be observed. First, when the PI controller is switched off (MLSS>2850g/m³), the remaining control (Q_u=0.65*Q_{in}) is insufficient to maintain the MLSS concentration in the desired range and the MLSS concentration will quickly drop below 2500 g/m³. This contrasts with the simulation results for the Takács model where a ratio of 0.65 seems to be effective in controlling the MLSS concentration. The explanation for this lies in the much lower (but more realistic) underflow concentration predicted by the Bürger-Diehl model during storm-weather as was illustrated in Figure 5. Second, when the PI controller is switched back on, the response of the Bürger-Diehl model to the applied control action is swift and large causing the MLSS concentration to almost immediately exceed the threshold of 2850 g/m³ and the PI controller to be switched back off. As can be seen around t=4 d in Figure 10, the MLSS concentration for the Takács model undergoes a much smaller increase when the same control action is applied.

To further understand the differences in behaviour between the two models, the responses to a step increase in the volumetric underflow flow rate Q_u is examined. To mimic the behaviour under high flow conditions, a step increase in Q_u from 18831 m³/d to 20000 m³/d was applied under a constant incoming flow of 30000 m³/d. (Note that investigating the step response during actual storm-weather (60000 m³/d) is not feasible since a long period of such increased flow conditions would upset the system too much making it no longer representative of realistic operating conditions.)

Figure 11 shows the resulting step responses for both models. On the left-hand side the absolute values of the MLSS concentrations are depicted, on the right-hand side the net step-response MLSS values are shown with respect to the steady-state value of each model before the step increase. For both models the MLSS concentration shows an initial steep increase followed by a much slower further increase until a new steady state is reached. The initial steep increase can be related to a period where the sludge that is present at the bottom of the clarifier is simply recycled at a higher rate. However, this sludge will not be replenished at the same velocity as it is pumped away causing the underflow concentration to drop and a switch to the second period where the system response slows down until a new steady-state value for the MLSS concentration is reached.

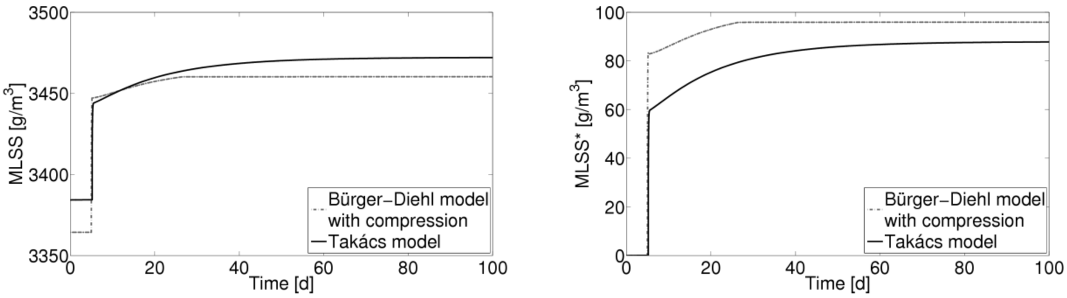

Figure 11: Response of the MLSS concentration in the first activated sludge tank to a stepwise variation in the underflow rate from 18831 m³/d to 20000 m³/d with a constant incoming flow of 30000 m³/d. MLSS* means the net step response with respect to the initial steady state.

With respect to the different response of both models to the control actions in Figure 10, it can be seen from Figure 11 that the initial steep increase in MLSS concentration is 30% larger for the Bürger-Diehl model compared to the Takács model. This causes the very swift increase in the MLSS concentration for the Bürger-Diehl model when the PI controller becomes active. Due to a combined effect of compression settling that causes a higher sludge blanket and the additional layers in the underflow region, more sludge is present in the SST when using the Bürger-Diehl model. Consequently, it takes somewhat longer before the underflow concentration will be affected and the settling sludge flux to the bottom layers becomes limiting. Hence, due to the under prediction of the SBH in the Takács model, the response to the control action is wrongly predicted and the controller will likely not work well when implemented in reality.

Hence, when the Bürger-Diehl model is applied to describe the settling-compression behaviour, an appropriate control strategy for the underflow concentration would combine a constant-ratio controller with a higher ratio and a PI-controller with more conservative tuning. Figure 12 shows the manipulations in underflow concentration and the MLSS concentration when a control action with a constant ratio of 0.75 and a PI controller with parameter values K_p=1 and τ_I=5 is applied in the Bürger-Diehl model. The control strategy for the Takács model is the same as in Figure 10. The large dilution in MLSS concentration that was observed in the open loop simulation results of Figure 8 is successfully counteracted by the applied control strategies. Due to the lower PI settings, much lower control actions for the underflow concentration are now applied during the storm event. This will not only influence the recovery period of the MLSS concentration but will also affect the cost calculations in the BSM model.

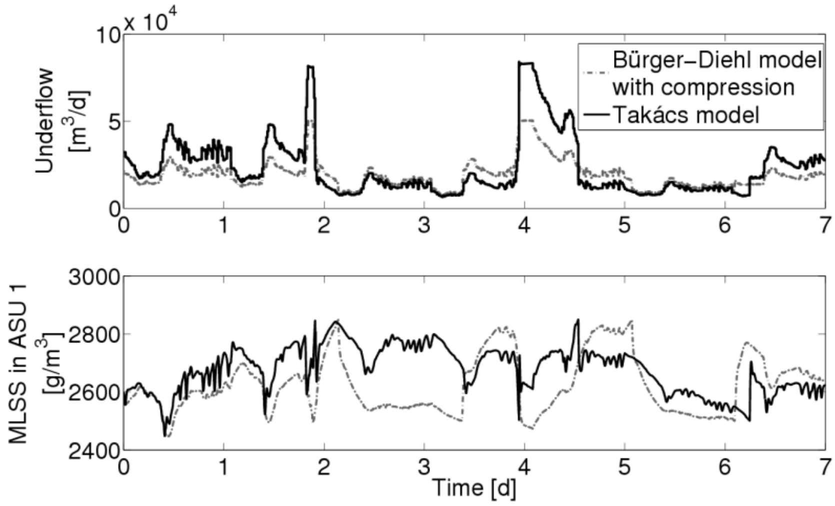

Figure 12: Dynamic simulation with the implementation of an MLSS control strategy (Q_u=0.65*Q_{in} + PI controller with K_p=10 and τ_I=1 for Takács and Q_u=0.75*Q_{in} + PI controller with K_p=1 and τ_I=5 for Bürger-Diehl). Manipulations in underflow rate (top) and MLSS concentration in the first activated sludge tank (bottom) under storm-weather conditions.

These results show that the choice of settler model can notably influence the evaluation of proposed control schemes. Since a real SST typically undergoes a significant increase in the SBH during storm-weather, thereby storing additional sludge in the system, its response to an increase in the underflow rate can be more extreme than would be predicted by the Takács model as the latter underpredicts the elevation in the SBH. Consequently, operating a real SST calls for more conservative control parameters than would be suggested by the Takács model. Hence, switching to more advanced settler models can potentially benefit the development of many future operation and control strategies. Moreover, this would allow for more advanced control strategies to be developed (for example control on the SBH in order to operate the system at higher sludge concentrations).

Practical implications of switching to a more advanced settler model

As the Takács model depends on the numerical dispersion (which is inherent in the model structure) for its simulation results, it should only be used with a 10-layer discretisation (as this approximately mimics dispersion under dry-weather). However, Jeppsson and Diehl (1996) demonstrated that a discretisation with 10 layers is too coarse an approximation to capture the detailed dynamic behaviour of the settler. By applying the Godunov scheme for the settling flux and handling the compression term in a mathematically sound way, the Bürger-Diehl model ensures that increasing the number of layers will result in a more accurate approximation of the governing PDE thus producing smaller errors in the underflow concentration. Note that for reasons of comparison, all simulations of the Bürger-Diehl model in this contribution have been performed with the same coarse discretisation level as is required for the Takács model. Their accuracy could thus easily be further improved by using a finer discretisation.

An important aspect in this context is to be able to quantify the added value of an increasing number of layers on the model accuracy. How many layers are needed to obtain a satisfying approximation of the analytical solution of the PDE? This was investigated by comparing simulations at different discretisation levels to a reference simulation with a very fine discretisation (360 layers), which is assumed to be a close approximation of the exact solution. Simulations were performed under both dry- and wet-weather conditions. The numerical errors in the underflow concentration were quantified by calculating the relative error at each time point t_i as follows:

$$RE\ (X_{\mathrm{u}}, t_i) = \frac{\left|X_{\mathrm{u},360}(t_i) - X_{\mathrm{u},N}(t_i)\right|}{X_{\mathrm{u},360}(t_i)}$$

with $X_{\mathrm{u},N}$ the concentration in the underflow, N the discretisation level and $X_{\mathrm{u},360}$ the underflow concentration of the reference simulation with 360 layers.

Calculating the numerical errors on the sludge blanket height is less straightforward since the SBH is limited to the layer intervals as determined by the discretisation. Moreover, as the SBH can be zero, the errors are simply quantified as absolute errors:

$$AE\ (SBH, t_i) = |SBH_{360}(t_{\mathrm{i}}) - SBH_{\mathrm{N}}(t_{\mathrm{i}})|$$

Unlike the underflow error, the error on the effluent concentration will not propagate throughout the system. Furthermore, accurate predictions of effluent concentrations in a 1-D model are currently still troublesome as 1-D models do not include discrete settling behaviour. Therefore the numerical error on the effluent concentration is not shown here.

Figure 13 shows the numerical errors in the underflow concentration and the SBH for simulations with the Bürger-Diehl model with compression. During dry-weather, the errors in the underflow are quite small, even for the 10-layer discretisation. However, during wet-weather, when the underflow concentration increases rapidly, the error for the 10-layer discretisation augments up to an average of approximately 10%. By using a 30-layer discretisation this error is reduced to less than 5%. Note that the numerical error becomes even worse when compression settling is not considered, since compression somewhat dampens the variations in the underflow concentration.

Also for the SBH a 10-layer discretisation (with a minimum variation of 40 cm) is clearly quite coarse to describe the dynamic behaviour. The numerical error reduces significantly when a 30-layer discretisation is applied.

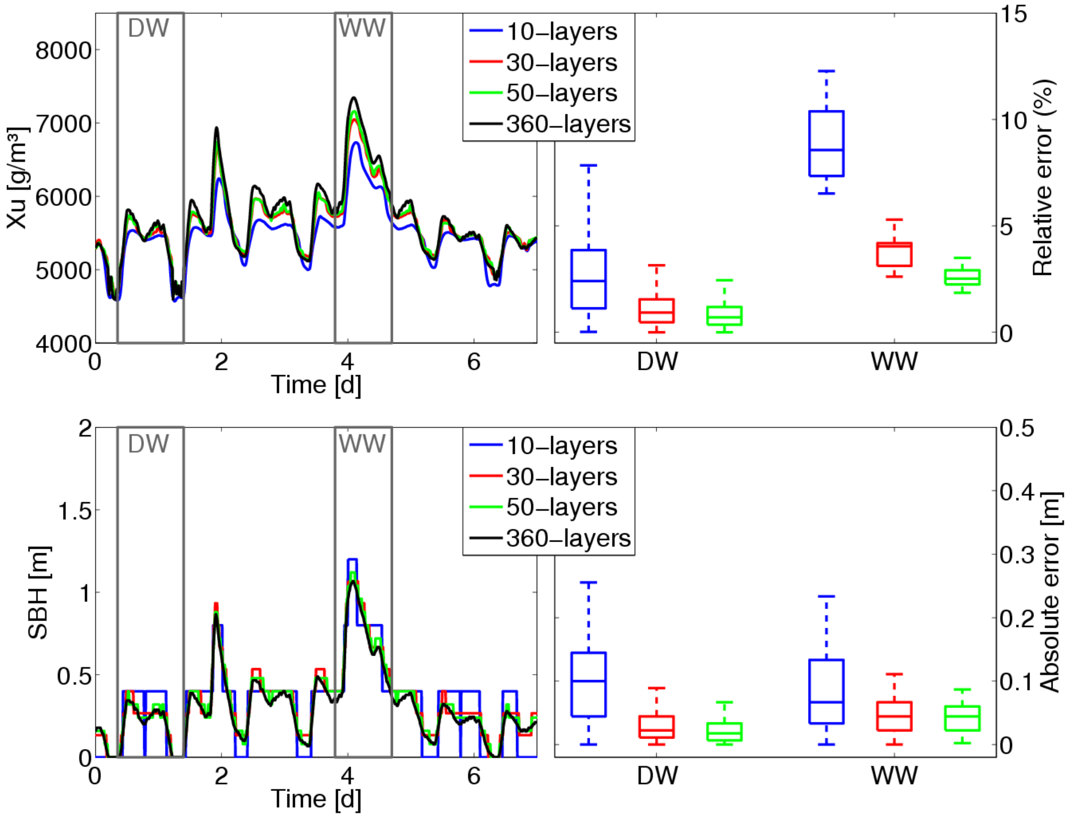

Figure 13: Simulated underflow concentrations with corresponding relative numerical errors (top) and simulated sludge blanket heights with corresponding absolute numerical errors (bottom) for different discretisation levels in dry- and wet-weather conditions (DW and WW).

However, more accurate predictions will inevitably come at a cost of increased simulation time. Not only do the computations around each layer increase with the added layers at each time step, the maximum allowed time step of the numerical scheme to ensure a stable and correct solution becomes smaller as the number of layers increases. For explicit fixed-step solvers (such as Euler or RK4) the maximum allowed time step is restricted by the so-called CFL condition, which unfortunately restricts the time step substantially when compression or dispersion is included. We refer to Bürger et al. (2013) for the details. In a recent publication Diehl et al. (2014) compared different ODE solvers with respect to their efficiency for the simulation of BSM1 with the Bürger-Diehl model under storm-weather conditions. Moreover, they introduced a semi-implicit time-discretisation method for which the simulation time with a 30-layer discretisation was shown to be approximately 7 times faster than a standard explicit solver such as Euler (placing it in the same range of computational effort as a 10-layer simulation with an explicit solver).

These results show that the currently used Takács model can be replaced by the Bürger-Diehl model providing a reliable alternative without having to make too many sacrifices with respect to simulation time. Consequently, from the results presented in this section, it is recommended to use a discretisation with at least 30 layers for simulations where the SST is coupled to one or more biological reactors. With a discretisation of 30 layers, the relative errors on the underflow concentration and SBH are reduced significantly while the simulation time is still acceptable. If more detailed simulation results are required from the modelling study or when the settler is modelled as a stand-alone system, the number of layers is recommended to be increased in order to have more accurate predictions.

CONCLUSIONS AND PERSPECTIVES

In this contribution, the impact of the new Bürger-Diehl settler model on operation and control of a WWTP in comparison to the traditional Takács model is investigated by using the Benchmark Simulation Model No. 1.

- Open and closed loop simulations were performed with both settler models during storm weather conditions and the simulated underflow concentration (X_u) and sludge blanket height (SBH) were compared to online data of the WWTP of Eindhoven. It was shown that the Takács model overpredicts the variations in X_u and underpredicts the SBH elevation whereas the Bürger-Diehl model provides more realistic predictions of X_u and SBH behaviour by accounting for compression settling and explicitly modelling the underflow region.
- The impact of the different settler models on the sludge inventory and conversion rates in the bioreactors was investigated as poor predictions of the recycled biomass force modellers to calibrate kinetic parameters for the wrong reasons. A difference of almost 20% for the predicted nitrification rate was observed between the two settler models during storm weather indicating that the choice in settler model influences the performance of the entire treatment plant.
- An MLSS-based control strategy was developed and implemented. Simulation results showed that operating an SST calls for more conservative control parameters than would be suggested by the Takács model due to the under prediction of the SBH elevation in the latter model. In order to improve operation and control of WWTPs, we need to step away from traditional layer models towards more sophisticated models such as the Bürger-Diehl model.
- Although the Bürger-Diehl model is not associated with a fixed number of layers, we have found that a discretisation of the model with 30 layers provides an acceptable trade-off between model accuracy and the required simulation time.

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