# Impact of reactive settler models on simulated WWTP performance

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**Abstract** Including a reactive settler model in a wastewater treatment plant model allows representation of the biological reactions taking place in the sludge blanket in the settler, something that is neglected in many simulation studies. The idea of including a reactive settler model is investigated for an ASM1 case study. Simulations with a whole plant model including the non-reactive Takács settler model are used as a reference, and are compared to simulation results considering two reactive settler models. The first is a return sludge model block removing oxygen and a user-defined fraction of nitrate, combined with a non-reactive Takács settler. The second is a fully reactive ASM1 Takács settler model. Simulations with the ASM1 reactive settler model predicted a 15.3% and 7.4% improvement of the simulated N removal performance, for constant (steady-state) and dynamic influent conditions respectively. The oxygen/nitrate return sludge model block predicts a 10% improvement of N removal performance under dynamic conditions, and might be the better modelling option for ASM1 plants: it is computationally more efficient and it will not overrate the importance of decay processes in the settler.

**Keywords** Activated sludge; ASM1; modelling; reactive settler; sedimentation; wastewater

## Introduction

Models of activated sludge treatment systems are widely used tools for benchmarking, diagnosis, and design. The complete model consists of a stoichiometric and kinetic reaction matrix component, as given in the ASM series (Henze *et al.*, 2000), and a hydraulic component. The hydraulic component describes tank volumes, tank behaviour (e.g. mixed, plug-flow, variable volume etc.) and the liquid flow rates in between tanks, such as return sludge flow rate and internal recycle flow rate. The secondary settler is normally part of the hydraulic model component, and varies in complexity. At an applied level, these vary from simple ideal separators, with no retention time, to the one-dimensional layered settler of Takács *et al.* (1991), which will include hydraulic transport of soluble components via a stirred-tanks-in-series representation.

It is still an assumption in most simulation studies that no reactions take place in the settler, although reactive settler models, obtained for example by combining the Takács settler model with the Activated Sludge Model No. 1 (ASM1; Henze *et al.*, 2000), have been available for quite a while (Watson *et al.*, 1994). In many full-scale plants a considerable amount of the sludge is stored in the bottom of the settler (Siegrist *et al.*, 1995). The assumption that this volume is effectively inert with respect to oxygen and nitrate removal, as well as biomass decay, may not be valid. This was demonstrated by Koch *et al.* (1999),

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where it was shown that 19% of the total incoming nitrogen was removed by denitrification in the secondary settler. In some cases biological activity in the settler is included in a treatment plant model by adding on an extra activated sludge tank to simulate the conversions in the sludge blanket (Siegrist *et al.*, 1995; Koch *et al.*, 1999). However, a detailed analysis of the effect of considering biological activity in the settler on the simulated plant performance is not available. This paper presents a simulation case-study for ASM1, comparing two methods for describing biological activity in the settler: (1) insertion of an extra model block in the return sludge line, allowing heterotrophic biomass growth to consume oxygen and a user-defined fraction of nitrate in the return sludge; (2) a reactive one-dimensional settler model, obtained by combining the settler model of Takács *et al.* (1991) with the ASM1 model.

## Methods

### Settler models

Model development and simulations were done in a Matlab/Simulink environment (Mathworks, Inc). Three different approaches for describing the settler (Figure 1) are compared in the simulations. The non-reactive one-dimensional Takács settler model (Takács *et al.*, 1991) was used as a reference model. This is a layered model (normally 10 layers), with hydraulic transport of solubles by stirred-tanks-in-series, and hydraulic and settling transport of particulates (Eq. 1). The settling velocity model describes both clarification and thickening.

$$v_{sj} = v_o \cdot e^{-r_h \cdot X_j^*} - v_o \cdot e^{-r_p \cdot X_j^*} \quad \text{and} \quad 0 \leq v_{sj} \leq v_{00} \tag{1}$$

where: $v_{sj}$ = settling velocity of the solids in the layer $j$ (m/d); $v_o$ = maximum Vesilind settling velocity (m/d); $v_{00}$ = maximum practical settling velocity (m/d); $r_h$ = hindered settling parameter ($m^3/g$); $r_p$ = flocculent settling parameter ($m^3/g$); $X_j^* = X_j - X_{min}$ ($X_j$ = TSS concentration in layer $j$ ($g/m^3$); $X_{min} = f_{ns} \cdot X_{in}$; $f_{ns}$ = non-settleable fraction of $X_{in}$ and $X_{in}$ = TSS concentration in the feed flow ($g/m^3$). The Takács model parameters used here are similar to the ones reported by Copp (2002).

In a second model, the Takács settler model was combined with an extra model block in the return sludge line (Figure 1). This block is an empirical, algebraic elimination of oxygen/nitrate ($O_2/NO_3$) via heterotrophic growth. It therefore results in an increase of heterotrophic biomass ($X_{BH}$). All oxygen, and a user-defined fraction of nitrate ($f_{Sno}$; set to 0.8 here) is consumed. COD is sourced in order from readily biodegradable soluble organics ($S_S$), and slowly biodegradable particulate organics ($X_S$). Nitrogen for growth is sourced in order from ammonia ($S_{NH}$), soluble organic nitrogen ($S_{ND}$), and particulate organic nitrogen ($X_{ND}$). Therefore, conversion may be limited by available electron acceptors ($S_O$, $S_{NO}$), available COD ($S_S$, $X_S$), or available reduced nitrogen for growth ($S_{NH}$, $S_{ND}$, $X_{ND}$).

A third settler model was developed based on the Takács model (Figure 1), extending the description of suspended solids (TSS) sedimentation and transport of soluble

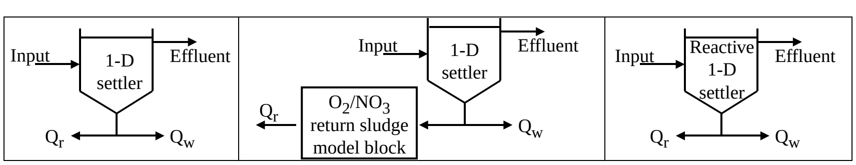



**Figure 1** Illustration of the different settler models. Left: non-reactive Takács settler; Middle: non-reactive Takács settler + $O_2/NO_3$ return sludge model block; Right: reactive ASM1 Takács settler

components available in this reference model with the full set of ASM1 equations (Henze *et al.*, 2000). As a result, each layer of this reactive settler model acts as an activated sludge tank in the simulations.

#### ASM1 case study

The IWA/COST simulation benchmark plant was selected as a case study to investigate the effects of considering biological activity in the settler in the treatment plant model. The plant, a predenitrification system consisting of two anoxic reactors, three aerated reactors and a settler (see Figure 2), is described in detail in Copp (2002). Reactor volumes and flow rates are indicated in Figure 2. The settler volume was 6000 $m^3$ (depth $=$ 4 m, cross-sectional area $=$ 1500 $m^2$).

#### Simulations

Three types of simulations were performed to compare the impact of the different settler model assumptions, using the same set of ASM1 model parameters (Copp, 2002) for all simulations:

(1) Steady-state benchmark simulations: the flow-weighted dry weather average influent composition of Copp (2002) was used as input to the plant, with no active controllers (open loop). The plant was simulated for 150 days until steady-state was reached. All three settler models were tested with a waste sludge flow rate ($Q_w$) at 385 $m^3$/d. The simulation with the reactive settler was repeated for $Q_w = 357.8$ $m^3$/d.

(2) Steady-state settler simulations: the ASM1 component concentrations at steady-state obtained with the reference plant (Takács settler) for reactor 5 (last aerated tank, see Figure 2) were used as input for simulations with the different settler models alone. Simulations were continued for 150 days, until steady-state was reached. These simulations were useful since they allowed comparison between the different settler models without interactions from the rest of the plant.

(3) Dynamic benchmark simulations: the dynamic dry weather influent profiles reported in Copp (2002) (and available from http:// www.benchmarkwwtp.org) were used as input to the open loop plant. The simulation procedure of Copp (2002) was followed: starting from the steady-state solutions obtained in step 1 (steady-state benchmark simulations), the plant was simulated for 28 days with dynamic influent data. The last week of data was used for plant performance evaluation.

### Results and discussion

#### Steady-state benchmark simulations

The models predicted an inventory of 20.2–20.3% of the total sludge in the settler. Comparing the three settler models, the reference simulation only allows soluble component removal in the 5 activated sludge reactors. Thus, at steady-state, inflow, effluent, and underflow of the settler have identical concentrations. For the simulation including the $O_2/NO_3$ block in the return sludge line the predicted soluble component concentrations in

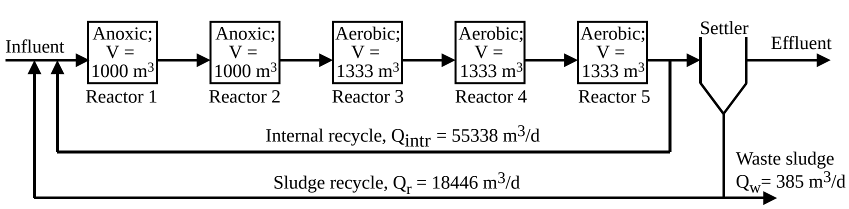



**Figure 2** Lay-out of the IWA/COST benchmark plant

inflow and underflow of the settler are different. For simulations with the reactive Takács settler model, the concentrations in inflow, effluent and underflow of the settler will be different. Both the inclusion of the $O_2/NO_3$ block in the return sludge line and the use of a reactive Takács settler were expected to improve the simulated overall nitrogen (N) removal efficiency of the treatment plant compared to the reference simulation, due to an improved denitrification efficiency. The simulation results at steady-state are summarised in Figure 3, and confirm this expectation.

Compared to the reference simulation, the $S_S$ concentration is slightly lower in the anoxic tanks for the simulation with the $O_2/NO_3$ block in the return sludge line, whereas it is considerably higher for the simulations with the reactive settler model. For the $O_2/NO_3$ block, this is because all $S_S$ is consumed in the settler underflow. For the reactive settler model, the $S_S$ concentration in the underflow is comparable to the reference simulation result. The $S_S$ concentration increase in the anoxic tanks observed for the reactive settler simulations is due to a lower denitrification rate in the anoxic tanks, since it coincides with a 10% lower heterotrophic biomass ($X_{BH}$) concentration and a more than 60% lower nitrate nitrogen ($S_{NO}$) concentration in the anoxic tanks. Clearly, the denitrification process is more efficient for the simulation with the reactive settler, because inclusion of the reactive settler in the plant model allows hydrolysis and denitrification to take place in the settler, similar to the anoxic activated sludge tanks. Figure 3 indeed indicates that the $S_{NO}$ in the settler underflow is more than 80% lower for the simulations with the reactive settler model, compared to the reference. The $S_{NO}$ concentration in the effluent is about 30% lower (a decrease from 10.42 to 7.14 mg N/l) compared to the reference simulation. For the $O_2/NO_3$ block, the effluent $S_{NO}$ concentration at steady-state is 8.40 mg N/l, whereas the $X_{BH}$ concentration in the plant is almost identical to the concentration obtained for the reference simulation. The simulated $X_S$ concentration for the $O_2/NO_3$ block is significantly lower compared to the other simulations, and this is mainly because $X_S$ may be utilised for heterotrophic growth in this $O_2/NO_3$ block, whereas $X_S$ generation from decay in the settler is assumed not to take place, contrary to the reactive settler.

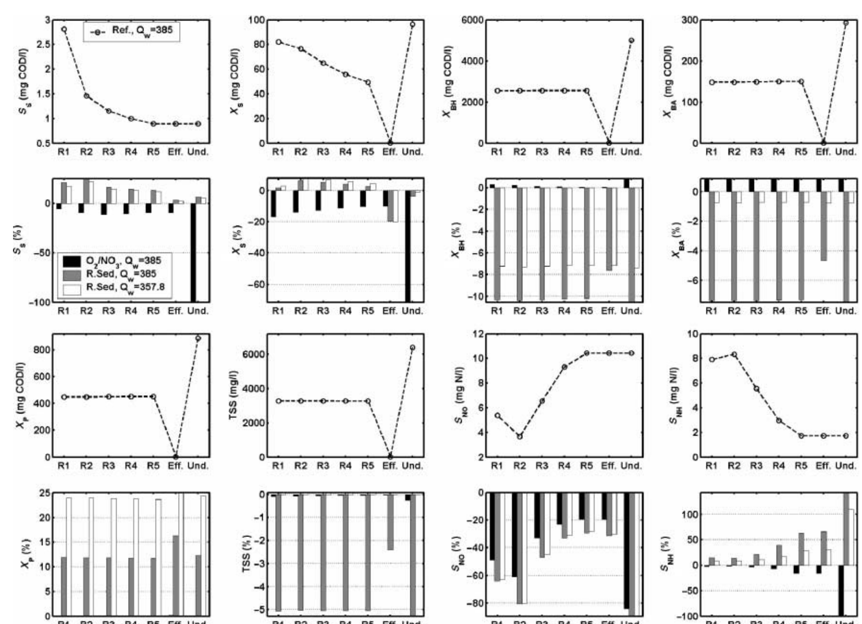





**Figure 3** Results of the steady-state benchmark simulations

The ASM1 component concentrations at steady-state in the different plant compartments (R = reactor, Eff. = settler effluent; Und. = settler underflow) obtained for the reference simulation are provided as separate graphs. The results for the other simulations (Takács settler with the $O_2/NO_3$ return sludge block, and the reactive ASM1 settler for two different waste sludge flow rates, 385 and 357.8 $m^3/d$) are provided in the bar charts as % deviation from the reference concentration values.

However, the predicted positive effect on the denitrification process resulting from including the reactive settler model is accompanied by a decrease in nitrification efficiency of the plant. This is caused by increased heterotrophic and autotrophic biomass decay, and the increased $S_{NH}$ production due to hydrolysis and ammonification in the settler. Decay reactions also explain the 10% lower $X_{BH}$ concentrations, the increased $X_P$ concentrations, and the lower TSS concentrations compared to the reference simulation. The effluent $S_{NH}$ concentration for the simulation with the reactive settler is 2.87 mg N/l, compared to 1.73 mg N/l for the reference simulation. The effect of decay reactions in the settler for the simulation with the reactive settler is also illustrated by the $S_{NH}$ concentration increase in the underflow compared to the settler inflow. In fact, this $S_{NH}$ concentration difference between inflow and underflow could easily be measured on a pilot- or a full-scale plant, and such measurements could thus provide some information to calibrate the hydrolysis processes in the model.

Including the $O_2/NO_3$ model block in the return sludge line does not involve effects of increased biomass decay on the N removal plant performance, since decay is assumed not to take place in the $O_2/NO_3$ model block. Some $S_{NH}$ is consumed during biomass growth. The result is a decrease of the effluent $S_{NH}$ concentration to 1.46 mg N/l, compared to 1.73 mg N/l for the reference simulation.

The overall effect of including the reactive settler model is as expected: the total effluent N concentration is 11.90 mg N/l for the simulation with the reactive settler, compared to 14.05 mg N/l for the reference simulation, or a decrease of 15.3%. Since including the reactive settler resulted in an overall decrease of the amount of TSS in the plant from 24,642 kg for the reference simulation to 23,407 kg, it was decided to tune $Q_w$ until the amount of TSS for the simulation with the reactive settler was close to 24,642 kg. This condition could be fulfilled by decreasing $Q_w$ from 385.0 to 357.8 $m^3/d$, thereby increasing the sludge age from 7.3 to 7.8 days. The increased sludge age resulted in an increase of the $X_{BH}$ and the autotrophic biomass ($X_{BA}$) concentration (see Figure 3), as well as a significant increase of the $X_P$ concentration. The latter reflects the increased biomass decay in the plant as a whole, as a consequence of the increased sludge age. For the simulated plant with $Q_w = 357.8\, m^3/d$, the effluent total N concentration was 11.43 mg N/l, or a reduction by 18.6% compared to the reference simulation, in addition to a 7% decrease of the sludge production. Thus, a first conclusion is that including a reactive settler model makes an important difference for the predicted N removal efficiency compared to a non-reactive Takács settler model.

The total effluent N concentration is 11.70 mg N/l for the simulation with the $O_2/NO_3$ return sludge block, which is comparable to the concentrations obtained with the reactive settler model. Thus, a second conclusion is that the N removal predicted with the reactive settler model can be approximated by combining a non-reactive settler model with an $O_2/NO_3$ return sludge block where no biomass decay is assumed to take place. Including the $O_2/NO_3$ return sludge block did not influence the predicted waste sludge production, compared to the reference simulation. With respect to model complexity, it was assumed that the approach with the $O_2/NO_3$ return sludge model block would be a compromise between the simplifications in the standard Takács model on the one hand, where the sludge in the settler is assumed not to be involved in any reactions, and the complexity of the reactive Takács model on the other hand, while still allowing the description of consumption of $S_O$ and $S_{NO}$ in the return sludge.

#### Steady-state settler simulations

Simulating the different settler models with identical inputs, without considering interactions with the activated sludge tank model, was performed to improve the understanding of the reactive sedimentation part of the models. Figure 4 provides some concentration profiles for $S_O$, $S_{NO}$, $S_{NH}$ and TSS for the reactive settler ($Q_w = 385\,m^3/d$). In the standard Takács settler model, under steady-state, concentrations of soluble components are equal throughout the settler, since there is no reaction. The profiles in Figure 4 illustrate that $S_O$ is rapidly depleted, whereas significant denitrification only takes place in the bottom layer of the settler, where the sludge concentration is about 6.4 g/l. Most of the hydrolysis and ammonification in the reactive settler also take place at the bottom of the settler, as indicated by the simulated increase of the $S_{NH}$ concentration in the bottom layer of the settler. This is quite logical, since hydrolysis involves the conversion of particulate material to soluble products, and in this case there is only a high concentration of particulate material at the bottom of the settler.

The evolution of the $X_S$, $X_{BH}$ and $X_{BA}$ concentrations in the settler is also illustrated in Figure 4. Since the particulate material will settle, there will be a concentration gradient, with increasing sludge concentrations from top to bottom. Therefore, it was preferred to show the ratio of each particulate model component (expressed in TSS units) to the TSS concentration in the respective settler layers, to illustrate the effect of the implementation of the ASM1 reactions in the settler. The $X_S$ fraction is highest at the feeding point (depth $= 1.8$ m), and decreases both towards the top and the bottom of the settler. This is the net result of hydrolysis and biomass decay. The $X_{BH}$ and the $X_{BA}$ fractions in the sludge do not change substantially in the settler. Thus, these simulations seem to indicate that the effect of biomass decay on the biomass concentrations in the settler is not that pronounced, especially for the autotrophs ($X_{BA}$). However, coupling the reactive settler model to the activated sludge tank model (see Figure 3) indicated that even small differences in biomass decay, introduced in this case by replacing a non-reactive settler by a reactive one, have a significant influence on the simulated plant performance. The reason for this is the presence of the death–regeneration cycle in ASM1, where biomass decay will lead to generation of new substrate for the heterotrophs. In ASM3 (Henze *et al.*, 2000) the death–regeneration cycle is no longer present, and it can thus be expected that

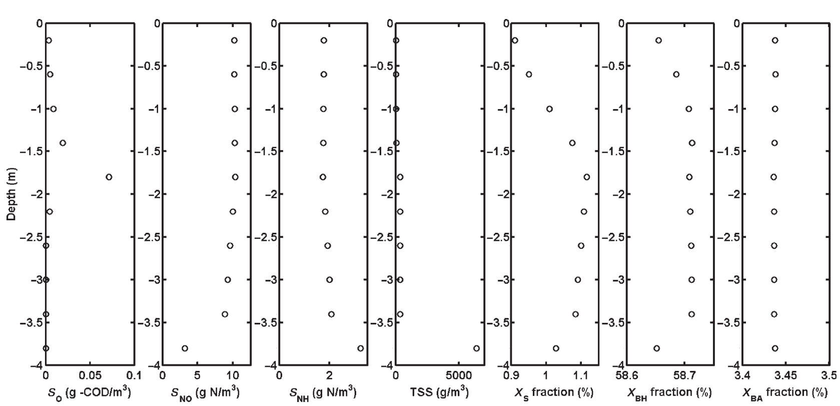



**Figure 4** Concentration profiles (steady-state) obtained with the reactive ASM1 settler model for $S_O$, $S_{NO}$, $S_{NH}$ and TSS. The influent feeding point is located at a depth of 1.8 m. The distribution of $X_S$, $X_{BH}$ and $X_{BA}$ fractions (expressed as % of total solids) in the settler are also shown

the impact on the plant performance of decay processes resulting from including a reactive ASM3 settler in a plant model will be less pronounced. Of course, it should be kept in mind that the observed effects will both depend on the kinetic parameter values used in the simulation and on the plant operating parameters (e.g. return sludge flow rate).

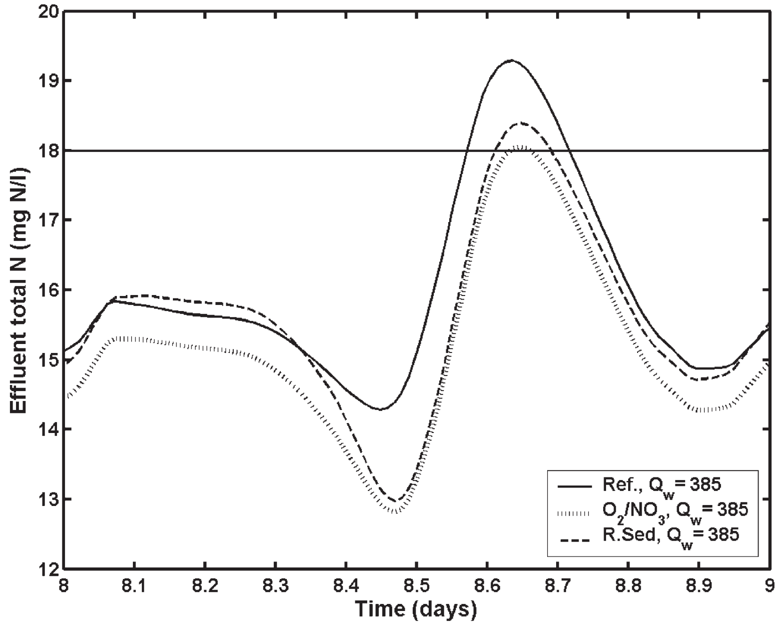
#### Dynamic benchmark simulations

The interpretation of the dynamic results will mainly focus on N removal, since the different settler model assumptions did not significantly influence effluent COD levels (see Table 1). A number of plant performance indicators, calculated according to the procedures proposed in Copp (2002), are provided in Table 1. Similar to the steady-state benchmark simulations, adding the $O_2/NO_3$ block to the simulation model results in a decrease of the predicted effluent total N concentration, mainly due to a decrease of the predicted effluent $S_{NO}$ concentration. However, the improvement resulting from the addition of the $O_2/NO_3$ block is only 10% for the dynamic simulations, compared to about 15% for the steady-state simulations. For the simulations with the reactive settler, the predicted total N removal improvement is only 7.4% for $Q_w = 385\,m^3/d$, and about 10% when $Q_w$ is decreased to $357.8\,m^3/d$. For both simulations, this is lower compared to steady-state simulation results.

Assuming an effluent total N limit of 18 mg N/l (Copp, 2002), the new settler models indicate almost 0% of time in excess of effluent limit, compared to 8.18% for the reference simulation (Table 1). The improved predicted N removal obtained by including the $O_2/NO_3$ block or the reactive settler is illustrated in Figure 5. However, the effluent total N dynamics for the $O_2/NO_3$ block and the reactive settler are somewhat different. During periods with low loads, i.e. from t = 8 to t = 8.4 days in Figure 5, the predicted N removal efficiency of the reactive settler model is similar to the N removal efficiency of the reference model, whereas it is better during the second half of the day. The $O_2/NO_3$ block predicts improved total N removal efficiency for the entire day. The main reason for these differences is increased decay in the ASM1 reactive settler. Figure 5 furthermore illustrates that up to 30% of the total amount of sludge in this plant will be present in the settler, a number that corresponds well with the 25% mentioned by Siegrist *et al.* (1995). An ASM1 reactive settler seems to be very sensitive to settler sludge inventory. The ASM1 is not very suitable for description of decay under anoxic or anaerobic conditions, as the decay rates are assumed to be fixed, independent of the redox conditions. Experimental evidence has clearly demonstrated that biomass decay rates depend on the electron acceptor availability, and this has been addressed in the ASM3 (Henze *et al.*, 2000). It was demonstrated earlier for the ASM2d model, essentially the ASM1 with phosphorus removal, that the predicted efficiency of the N removal processes improves significantly by including the more realistic assumption that decay process rates are electron acceptor dependent (Gernaey and Jørgensen, 2004).

**Table 1** Comparison of a number of effluent quality related indicators for the dynamic benchmark simulations

| Effluent quality indicator | Reference $Q_w = 385.0$ | $O_2/NO_3$ block $Q_w = 385.0$ | Reactive settler $Q_w = 385.0$ | Reactive settler $Q_w = 357.8$ |
|---|---|---|---|---|
| $S_{NO}$ (mg N/l) | 8.82 | 7.46 | 6.77 | 6.71 |
| $S_{NH}$ (mg N/l) | 4.76 | 4.67 | 5.72 | 5.28 |
| Kjeldahl N (mg N/l) | 6.75 | 6.61 | 7.71 | 7.29 |
| Total N (mg N/l) | 15.57 | 14.07 | 14.42 | 14.00 |
| Total COD (mg COD/l) | 48.29 | 48.25 | 47.95 | 48.34 |
| Total N limit violation (%) | 8.18 | 0.45 | 1.49 | 0.30 |



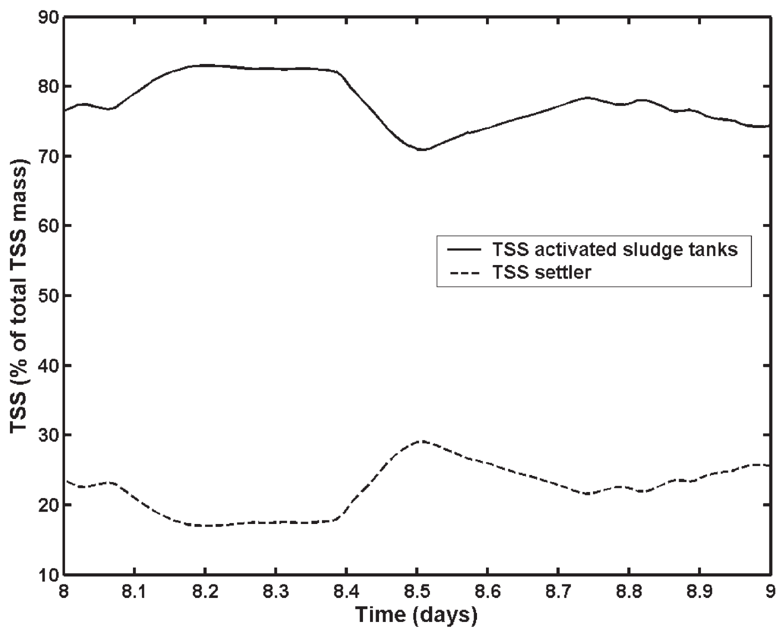




**Figure 5** Dynamic simulation results: Top: effluent total N concentration profiles for 1 day predicted with the reference model (Takács settler, no reactions), the $O_2/NO_3$ block combined with the Takács settler and the reactive ASM1 settler model for $Q_w = 385\,m^3/d$. Bottom: evolution of the TSS distribution between plant and settler during a dry weather day

Computationally, the $O_2/NO_3$ return sludge model block is also more efficient. It only leads to a 5% increase in computation time compared to the reference simulation (using the Matlab ode45 solver), whereas the reactive ASM1 settler model results in a 27% increase of the computation time.

Summarising, there are three processes that should be included in a reactive secondary settler. These are: (a) hydrolysis of particulates, (b) reduction of nitrate and oxidation of COD via heterotrophic growth, and (c) increased heterotrophic and autotrophic decay.

We have an empirical, algebraic model that expresses the first two by a simplified block, and an ASM1-based reactive settler model that represents all three. Especially the heterotrophic activity has been shown (Koch *et al.*, 1999), to have the most impact on plant performance, and is a key process. Increased decay is most likely also very important, especially in systems with long sludge ages. However, the simulation results indicated that ASM1 probably provides a poor representation for two reasons: (1) the presence of the death–regeneration cycle in ASM1; (2) the poor decay representation under low redox conditions, where decay rates are not reduced in the absence of $S_O$. As an illustration of this, the ASM1 based settler model presented here is very sensitive to sludge age. One proposed solution is the use of the ASM3, or another empirical (simpler) representation of decay. Experimental data is very important for further experimental verification of this feature, especially with variation in sludge age.



## Conclusions

Considering reactions in the settler when simulating a N removal treatment plant results in a 10–15% improvement of N removal predictions. For the ASM1 model, the use of an $O_2/NO_3$ model block in the return sludge line is probably a better option compared to a reactive ASM1 settler model. It is computationally more efficient and it will not overrate the importance of decay processes in the settler. Further experimental verification of the simulation results is needed.

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