Modelling of full-scale wastewater treatment plants with different treatment processes using the Activated Sludge Model no. 3

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Abstract In 1999 the Activated Sludge Model no. 3 (ASM 3) by the IWA task Group on Mathematical Modeling for Design and Operation of Biological Wastewater Treatment was presented. The model is used for simulation of nitrogen removal. On the basis of a new calibration of the ASM 3 with the easy degradable COD measured by respiration simulation runs of this paper have been done. In 2000 a biological phosphorus removal module by the EAWAG was added to the calibrated version of ASM 3 and is now serving the current requirements for modelling the enhanced biological P-removal. Only little experiences with different load situations of large-scale wastewater treatment plants were made with both new models so far. This article reports the experiences with the simulation and calibration of the biological parameters using ASM 3 and the EAWAG BioP Module. Three different large-scale wastewater treatment plants in Germany with different treatment systems will be discussed (Koblenz: pre-denitrification; Hildesheim: simultaneous denitrification with EBPR; Duderstadt: intermediate denitrification with EBPR). Informations regarding the choice of kinetic and stoichiometric parameters will be given.

Keywords Activated Sludge Model no. 3; EAWAG-BioP-Module; simulation; nutrient removal; EBPR; full scale plant data

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Activated Sludge Model no. 3

The *Activated Sludge Model* No. 3 (ASM 3) was published in 1999 by the IWA Task Group on Mathematical Modeling for Design and Operation of Biological Wastewater Treatment (Gujer *et al*., 1999). Better possibilities to identify biological processes today have resulted in the development of the new model ASM 3 to simulate nitrification, denitrification and degradation of COD. Compared with the ASM 1 (Henze *et al*., 1987) the new model describes storage of organic substrates, decay of heterotrophic organisms was modeled by the endogenous respiration and smaller anoxic yields for the heterotrophic organisms were used. The process of Hydrolysis slowly degradable COD (XS) is not depending on redox conditions and has a smaller significance because the lysis process (with the production of slowly degradable COD) has been replaced by endogenous respiration. Hydrolysis of nitrogen has been combined with Hydrolysis of COD. The decay rates for endogenous respiration of heterotrophic and autotrophic organisms are reduced under anoxic conditions (Nowak, 1996; Siegrist *et al*., 1999). For the following simulations the calibrated version of ASM 3 by Koch *et al*. (2000) has been used. The main difference to the original publication (Gujer *et al*., 1999) is the fact that readily degradable COD is not measured by filtration but by respiration. Furthermore slowly degradable COD (X_S) includes soluble and particular components.

EAWAG Bio-P-module

The EAWAG Bio-P Module (Rieger *et al*., 2000) completes biological phosphorous removal to ASM 3. The perceptions of ASM 3 have been integrated in the BioP-module too. For this endogenous respiration replaces lysis, different yields for aerobic and anoxic conditions are used and anaerobic decay was also neglected for the PAOs. The model adds 11 additional processes to the ASM 3 to describe the EBPR. The fermentation of COD has been omitted because in municipal wastewater this process does not seem to limit the release of phosphate at anaerobic conditions. Glycogen as a additional substrate pool for growth is not taken in consideration as there could not be found a significant influence on the enhanced biological P-removal. The processes of chemical precipitation have been integrated additionally in SIMBA 3.3$^+$ (IFAK, 1999) in the way they are used in ASM 2d (1999).

Koblenz Wastewater Treatment Plant

The Koblenz wastewater treatment plant was extended until 1992 to a total number of inhabitants and populations equivalents of 320,000. The plant was designed as pre-denitrification and consists of a primary treatment, a first biological stage using trickling filter (only operated in the case of storm water flow) and a second biological stage with a usual aeration system. Rectangular tanks with horizontal flow are used for final clarification. The plant has two parallel lines that show a strong gradient of concentrations caused by the long tanks. Figure 1 shows the plant system.

Both lines of the aerated tank and the secondary clarifier were taken into consideration in the simulation, that was done with the calibrated version of Koch *et al*. (2000), so phosphorus removal was not modelled. Measured data was available in the influent with total COD and filtrated COD as well as readily degradable COD (average value measured by respiration). In the tank the total suspended solids, the concentrations of oxygen at different points in longish tanks (plug flow reactor) and the effluent concentrations of ammonia and nitrate were known for the simulation period (13.10–19.10.1994). The BOD/TKN-ratio at Koblenz in the influent is very low, as it is about three. The influent load of the new line is different from the old one, as the wastewater of paper production is dumped into the new line. The influent fractioning in % of total COD was as follows: 61.5% X_S, 10% X_I, 15% X_{BH}, 3.5% S_I. For the readily degradable COD exists measured data that shows that this fraction was 10% of total COD (measured by respiration) in the influent to the denitrification tank. The retention time is about 11 days.

The WWTP at Koblenz is not operated with enhanced biological phosphorus removal. Chemical precipitation was integrated in the simulation by taking in account the average precipitation sludge amount as additional part of TSS in the influent of the denitrification tanks. The total suspended solids in the aerated tank have been calculated different from the way it was done at WWTP Hildesheim. The original calculation of TSS in ASM 3 was used at Koblenz with good results.

Because of the fact that the tanks are quite long (e.g. 1:8 (width: length at the new line)) with high gradients of concentration (plug-flow) it was decided to model the plant with

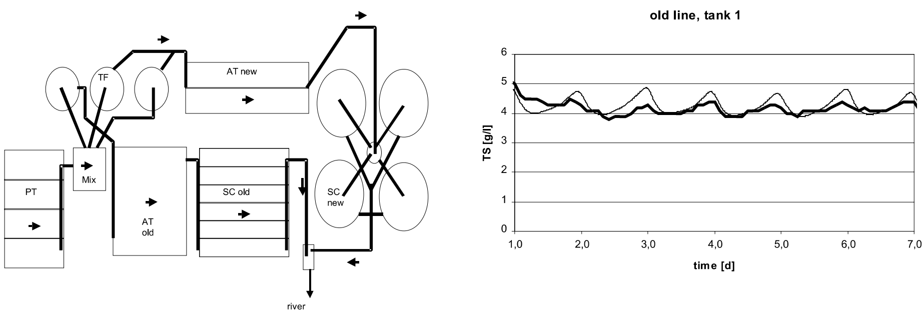

Figure 1 Wastewater treatment at plant Koblenz (right), simulated TSS [kg/m^3] in the old line, (thin line: simulated values, thick line: measured values)

several tanks in line. Measured data of oxygen concentration are available at six points (old line) and four points (new line), the aerated zone is simulated as six respectively four tanks. Average oxygen concentrations are especially in the old line quite high with 3.2 gO_2/m^3. Measured oxygen concentrations are used in the simulation by reading the data from files and comparing and adapting the oxygen values in the simulation with the measured data by PID-controllers.

The results of the simulation of the ammonia effluent values are shown in Figure 2.

For the adaptation the capacity of the nitrification was raised, as with the standard parameters of ASM 3 a sufficient nitrification could not be realised. For this the saturation coefficient of the nitrification for oxygen has been decreased. For different plants and models it was observed at the ISAH that the nitrification capacity with the standard set of biological parameters is modelled too small. For this the saturation coefficient for oxygen was reduced from 0.5g/m^3 to 0.13 g/m^3. In the old line the online data of the last day is faulty as the measurement unit was broken. The average ammonia concentration in the effluent of the aerated tank is simulated well. The dynamic values have the same tendency as the measured data.

The modelling of denitrification was more difficult at the WWTP Koblenz. The BOD/TKN-ratio of about three is quite low although the average nitrate effluent concentrations of 6g/m^3 are quite good, so denitrification in the secondary clarifier was integrated in the model with an additional tank of 20% of the total SC volume in the return sludge stream. Furthermore simulation revealed that the volume of the recycle stream to get back nitrate in the denitrification tank was measured wrong at first, as the quantity of nitrate returned even with total degradation was too small to fulfill the measured effluent data.

After increasing nitrification with the decrease of the saturation coefficient of oxygen $K_{O_2,aut}$ to 0.13 mg/l results could be calculated as shown in Figure 3

The saturation coefficient of oxygen $K_{O_2,Aut}$ has been decreased as only with this parameter nitrification at the plant at Hildesheim could be modeled well. As could be seen from the picture the simulation results compared with measured data are quite good. The saturation coefficient of oxygen for the heterotrophic organisms hat been increased from $K_{O_2,Het}$= 0.2 to 0.5 g/m^3. Furthermore the reduction of the anoxic decay rate was set to the value

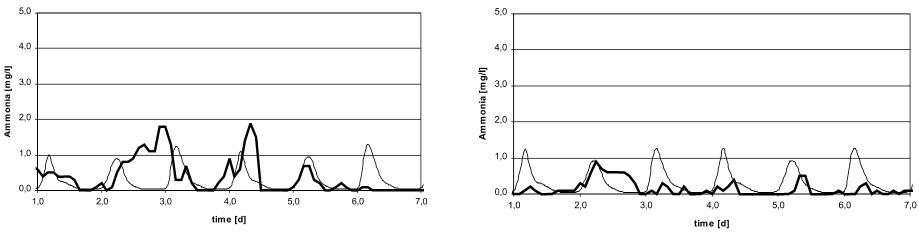

Figure 2 Results of the simulation and measured data of ammonia [g/m^3] with the ASM 3 within the validation period of 6 days in the old line (right), new line (left), (thin line: simulated values, thick line: measured values)

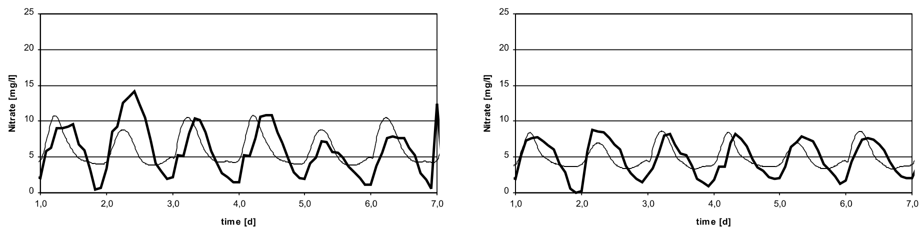

Figure 3 Results of the simulation and measured data of nitrate [g/m^3] with the ASM 3 within the validation period of 6 days in the old line (right), new line (left), (thin line: simulated values, thick line: measured values)

proposed by Koch *et al*. (2000) $\eta_{NO_3,end,Het} = 0.5$. This value was changed by Rieger *et al*. (2000) for the implementation of EBPR-processes, but at WWTP Koblenz we only model nitrification and denitrification.

In the diagrams it could be also seen that at the end of the validation period a difference exists between the time when simulated and measured peaks occur at the plant, which could be a hydraulic problem.

Hildesheim Wastewater Treatment Plant

The wastewater treatment plant at Hildesheim is built with a biological stage with nitrification, denitrification and biological phosphorus removal. The plant is run using the ISAH-process, the main asset of which is that the return-sludge is denitrified in a separate anoxic tank in order to prevent any possible impairing of the phosphate removal through return nitrate. If necessary, additional substrate can be fed from the anaerobic tank. Of the four lines planned for the activated sludge plant, two were built and started in July 1987 (Figure 4, left side), in order to use operation experiences for the construction and upgrading of the other two (Figure 4, right side), which both are running since 1997.

The WWTP at Hildesheim is operated like simultaneous denitrification. The plant is modelled with a two layer approach of Alex *et al*. (1998). The two layers exist principally for the whole length of the tank and have recycle streams separated from each other. The substance exchange can be done by definable exchange streams and additionally by the choice of velocity gradient between the two layers. With this gradient the mass balance of the substances is controlled. Additionally the substance exchange could be influenced by the definition of mixed streams between the two layers.

For the simulation of the plant at Hildesheim measured online-data of total COD, filtrated COD, TKN and Ammonia was used. The readily degradable COD was about 16% of the total COD. Additional online data was available in the effluent for ammonia, nitrate and PO_4-P. For the calibration of the TSS in the aerated tank we used a measured factor of 1.1 COD/TS.

In the following the plant has been simulated in two different periods of times. The first one models a period with a high plant loading before the extension of the plant in 1995, the second period shows the old line after upgrading the plant and much lower loading rates. It was possible to simulate both situations with small changes of the biological parameters.

Simulation of 1995 data (20.5.95–25.5.95) with high influent loading (SRT ~11 days)

This data set has been simulated yet with different models. The problem until now was the modelling of the phosphorus removal. Within a six-day-validation period without precipitation is found a relatively high peak of PO_4-P in the effluent, which always has been hard to simulate. The peak is about four and a half times higher than the average effluent data.

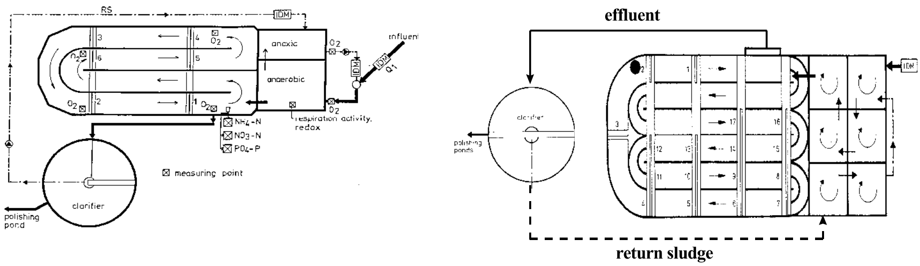

Figure 4 Flow sheet of the two types of lines (left = running since 1987, right = upgraded and running since 1997) at the wastewater treatment plant at Hildesheim

The simulation (ASM 3 with EAWAG BioP-module) shows an excellent correspondence. The influent fractioning in % of total COD was as follows: 49% X_S, 15% X_I, 9% X_{BH}, 11% S_I and 16% S_S. The simulated results of the hard to hit PO_4-P effluent concentration peak were very good. The results are presented in the Figures 5 and 6.

The effluent values at Hildesheim concerning nitrogen removal have been simulated without greater adaptation of biological parameters. Only the nitrification was increased by decreasing the saturation coefficient of oxygen $K_{O_2,Aut}$ to the value of 0.13 gO_2/m^3, which was also done at WWTP Koblenz to get a better flow description.

Figure 6 shows the simulated and measured PO_4-P data. It could be seen that the PO_4-P-peak was modelled very well. This was possible because of a change of two biological parameters. The polyphosphate storage rate q_{PP} was increased from 1.5 d^{-1} to 2.3 d^{-1} and the maximum storage of polyphosphate K_m was changed from 0.2 g/m^3 to 1g/m^3. As this maximum content of phosphate could not be reached in reality we examined that the reached concentration of polyphosphate of PAO in simulation still were lower than the measured values of 0.2–0.34 gP/gCOD. For this the adaptation should be possible.

The other picture shows the results of the nitrate effluent values that reached without any change of parameters and have good quality compared with the measured data.

A research at the ISAH (Wichern *et al*., 1999) showed that the effluent results concerning PO_4-P at Hildesheim were also reached well with the model of the university of Delft (Murnleitner *et al*., 1997). Although the PO_4-P-peak has not been simulated at 3 days immediately the average effluent values were modelled without any change of biological parameters for the enhanced biological phosphorus removal.

Simulation of 1997 data with low influent loading after upgrading the plant (SRT ~38 days)

After the upgrading of the WWTP at Hildesheim the influent load of the older line was much lower than before (influent fractioning in % of total COD: 54% X_S, 13% X_I, 9% X_{BH}, 7% S_I and 17% S_S). The sludge retention time was raised up to 38 days. As a result the effluent concentrations of all soluble components were lower than in the first period. The average PO_4-P effluent concentration was about 0.2 g/m^3 which is normally difficult to model. The results for nitrate and phosphate with the ASM 3 + BioP module are presented in Figure 7. Effluent values of ammonia were simulated well, so they are not shown here.

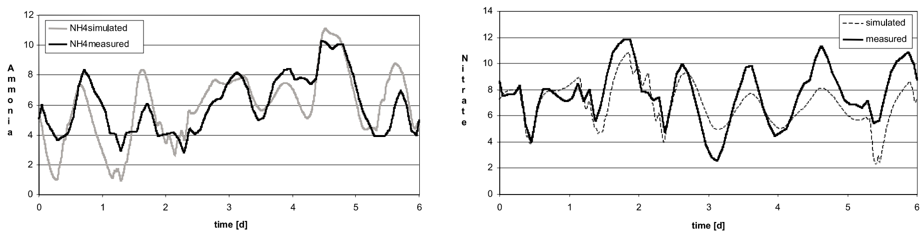

Figure 5 NH_4-N and NO_3-N in [g/m^3] effluent curve simulated and measured for a representative load at the wastewater treatment plant at Hildesheim

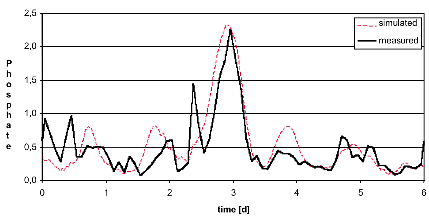

Figure 6 PO_4-P-effluent curve simulated and measured for a representative load at the wastewater treatment plant at Hildesheim

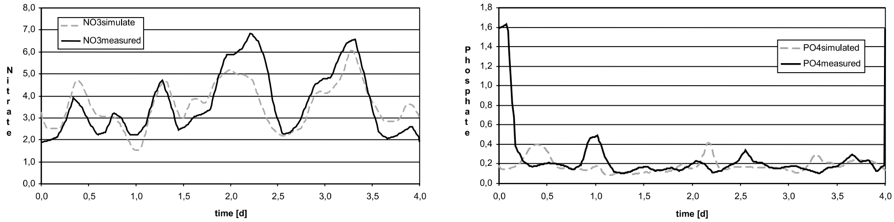

Figure 7 NO_3-N and PO_4-P-effluent curves [g/m^3] simulated and measured at the wastewater treatment plant at Hildesheim (1997) with low influent load

As it could be seen in the pictures the results for nitrate concerning the dynamic and the absolute quality were very good. The average PO_4-P data was also reached, but the dynamic modelling shows deviations yet. During calibration of the phosphorus removal it was significant that the elimination responds very sensible to the parameter $K_{PO_4,PP}$ in the EBPR-module from EAWAG, that was reduced from 0.2 g/m^3 to 0.12 g/m^3 and leads to lower effluent values of PO_4-P.

Duderstadt Wastewater Treatment Plant

The wastewater treatment plant at Duderstadt was designed as intermitted denitrification with an integrated pre-anaerobic volume in the round aerated tank to establish enhanced biological phosphorous removal. The plant is operated with a high sludge retention time of about 29d (simulation period 2.–9.10.1994) and without a primary settling tank. For this higher concentrations of particular components in the influent to the aerated tank can be expected. For simulation an influent fractioning in % of total COD was used as follows: 57% X_S, 24% X_I, 10% X_{BH}, 3% S_I and 16% S_S. The intermittent aerated tanks are operated by a control of oxygen and ammonia.

The influent values of TSS calculated by ASM 3 have been adapted to measured data of TSS by adding an additional mineral fraction into the influent.

For Duderstadt again nitrification and phosphorus removal was increased. The saturation coefficient of oxygen $K_{O_2,Aut}$ was set to the value of 0.18 gO_2/m^3 to model average effluent values of ammonia. As it could be seen in Figure 8 (left picture) the dynamic simulated curve of ammonia did not reach the minimum effluent values of 0mg/l. A change of the maximum growth rate for autotrophs $\mu_{Aut,max}$ and of the saturation coefficient of ammonium $K_{NH,Aut}$ also didn't show better results. Nitrate and PO_4-P effluent concentration showed better results as can be seen in Figure 7 (right picture).

For this denitrification was increased with the saturation coefficient of oxygen for the heterotrophic organisms $K_{O_2,Het}$= 0.5 g/m^3 and the reduction of the anoxic decay rate was set to the value proposed by Koch *et al*. (2000) $\eta_{NO_3,end,Het}$ = 0.5, which was also done at Koblenz.

The changed parameters for Hildesheim also showed good modeling results for EBPR at Duderstadt (Polyphosphate storage rate q_{PP} increased from 1.5 d^{-1} to 2.3 d^{-1}, maximum storage of polyphosphate K_{max} from 0.2 g/m^3 to 1g/m^3).

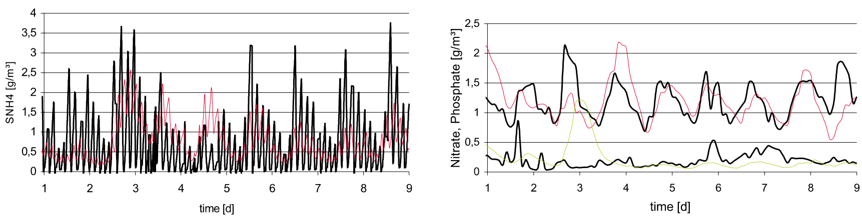

Figure 8 NH_4-N-effluent curves [g/m^3] (left figure), NO_3-N and PO_4-P-effluent curves [g/m^3] (right figure, NO_3-N upper curves, PO_4-P lower curves) simulated and measured at the WWTP at Duderstadt (1994), thin line: simulated values, thick line: measured values

Changed biological parameters

In the following there are presented the values of the kinetic and stoichiometric parameters that were adapted to simulate the measured data of the plants at Koblenz, Hildesheim and Duderstadt. Basis for the parameters are the publications of Koch *et al*. (2000), who had done changes in the original parameters of ASM 3 and Rieger *et al*. (2000).

Significant in the table above are two facts. In the five studied simulations (two lines with different loadings at Koblenz, two loadings at Hildesheim and one at Duderstadt) we had to adapt the nitrification for a better flow description that was simulated worsen with the standard parameters. That was done with the decrease of the saturation coefficient for oxygen of the autotrophic organisms $K_{O_2,Aut}$. The change of the parameter $K_{O_2,Aut}$ results from initial difficulties to model the surface aerated recirculation ditch at Hildesheim with adaptation of $K_{NH,Aut}$, that did not show good results.

Also the enhanced biological P-removal was increased at the plants at Hildesheim and Duderstadt. Adapted were two coefficients: the polyphosphate storage rate q_{PP} to the value of 2.3 and the maximal storage of polyphosphate K_{max} to 1.0. Although the maximum storage of polyphosphate was increased the simulated polyphosphate contents of PAO in simulation did not exceed normal maximum contents of of 0.2–0.34 gP/gCOD (e.g. Rieger *et al*., 2000b) recommended also in ASM 2d or the EAWAG BioP-module. So K_{max} was used as calibration parameter for EBPR.

Conclusions

In this paper different large scale treatment plants have been modelled with the Activated Sludge Model no. 3 (Gujer *et al*., 1999) in the calibrated version of Koch *et al*. (2000) and the EAWAG-BioP-Module (Rieger *et al*., 2000). Five different loadings were examined at Koblenz (predenitrification, two lines with different loadings, SRT~11d), at Hildesheim (simultaneous denitrification, EBPR, two different loadings with SRT~11d and 38d) and at Duderstadt (intermediate denitrification with EBPR, SRT~29d). Information on the plants, their loading situation and the actual fractioning of COD used for simulation are presented. Denitrification in the secondary settling tank was taken in account for all plants.

Good simulation results were achieved using the new models. Easy degradable COD (S_S) in all simulations runs was measured by respiration not by filtration, as suggested in the original publication of the ASM 3. For the typical German wastewater of the three simulated plants it can be recommended to increase nitrification and EBPR to establish suficient biomass for degradation of ammonia and phosphate. Good experience was made with the EAWAG-BioP-Module, that was able to model strong variations of the effluent

Table 1 Changed biological parameters for the simulation of the plants at Hildesheim, Duderstadt and Koblenz, compared with the published values

	ASM 3, Gujer et al. (1999)	**Koch et al. (2000)/Rieger et al. (2000)**	**Hildesheim '95/'97**	**Duderstadt '94**	**Koblenz (2 lines, different loadings, '94)**
Nitrification					
$K_{O_2,Aut}$ [g_{O_2}/m^3]	0.5	0.5	**0.13/0.13**	**0.18**	**0.13**
Denitrification					
K_{O_2} [g_{O_2}/m^3]	0.2	0.2	0.2/0.2	**0.5**	**0.5**
$\eta_{NO_3,end,Het}$ [–]	0.5	0.50/0.33	0.33/0.33	**0.5**(1)	**0.5**(1)
P-Elimination					
$K_{max,PAO}$ [g_P/g_{CSB}]	–	0.2	**1.0 /1.0**	**1.0**	–
q_{PP} [1/d]	–	1.5	**2.3/2.3**	**2.3**	–
$K_{PO_4,PP}$ [gP/m^3]	–	0.2	0.2/0.11	0.2	–

(1)recommended value of Koch *et al*. (2000)

PO_4-P values at normal sludge retention times of ~11d as well as low PO_4-P concentrations at high SRT of ~38d.

Acknowledgements

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