Calibration of a Dynamic Model of a Full Scale Wastewater Treatment Plant for Prediction of the Potential of Combined In-line Hydrolysis with Predenitrification

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Abstract. Combining sludge hydrolysis with predenitrification is a promising method to remove nitrogen and decreased use of external carbon content in wastewater. The Klagshamn wastewater treatment plant plans to alter the primary settler into an in-line hydrolysis basin with subsequent predenitrification to reduce the nitrate load into the overstrained moving-bed biofilm reactor. A reference scenario, which included annual data from the process control system, was established and calibrated with the operational findings from the plant in 2007 to form a dynamic wastewater model. A method for generating a complete annual data set based on laboratory values was established and implemented with the model. The simulated results agreed well with Klagshamn's actual operation. In addition, the simulated results of the proposed in-line hydrolysis basin were used to evaluate the potential for predenitrification. The results with hydrolysate showed that an additional 40 t·a^{-1} of nitrogen could be denitrified compared to the reference scenario.

Introduction – *SNE Header Unnumb*.

The Klagshamn municipal wastewater treatment plant (WWTP) in Sweden uses mechanical and chemical treatment as the primary treatment step. Thereafter, carbon is removed and ammonium is converted into nitrate in the activated sludge (AS) process. Nitrogen removal occurs in a subsequent moving-bed biofilm reactor (MBBR^{TM}) with ethanol as an external carbon source functioning as an energy supply for the denitrifying heterotrophic bacteria (Henze et al., 2002).

In 1998, a study predicted that the Klagshamn WWTP would reach its maximum capacity for nitrogen within 15 years due to the increasing number of connected households (Andersson et al., 1998).

A possible extension of the MBBR^{TM} volume or carrier-filling degree was determined to be too costly. Converting the WWTP into a chemical-free plant that could provide the required capacity is a major challenge. Therefore, Jönsson et al. (2008) performed a study investigating the predenitrification potential by applying primary sludge hydrolysis to provide the internal carbon source. A denitrification rate of 3.1 mg NO_3-N·(g VSS·h)$^{-1}$ for the hydrolysate was achieved, and 50% of the external carbon source could be saved. To reduce the nitrate load into the MBBR^{TM}, between 12.5% and 25% of the AS volume could be used for predenitrification. To determine the corresponding values in a full-scale application, dynamic variations such as flow, temperature and wastewater compound concentrations needed to be included in the dynamic wastewater modelling to evaluate possible scenarios for the Klagshamn WWTP. Dynamic wastewater modelling was able to effectively evaluate the AS process on other full-cale WWTPs (Brdjanovic et al., 2000; Larrea et al., 2000; Makinia et al., 2006). However, due to cost and time limitations, the characterisation of the wastewater compositions and variations are less satisfactory when modelling over a full year of operation.

In addition, the Swedish Environmental Protection Agency (NFS; 2000) stipulates that wastewater should be sampled on a 24 h flow- proportional basis, resulting in a limited number of samples that can be used for plant control. Therefore, the amount of analysed wastewater compounds (e.g. total chemical oxygen demand (CODt), total nitrogen (TN) and total phosphorous (TPt)) can vary and lead to limited data on some of the main wastewater components. A method for generating reasonable estimates of the missing wastewater compound concentrations over the course of a year needs to be established.

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This study presents a dynamic simulation containing configurations such as tank volumes, tank areas and pump capacities of the Klagshamn WWTP from 2007, which includes the year-round data for flow and temperature variations applied in the wastewater simulation tool EFOR (2003). A method for establishing a complete annual time series of the incoming wastewater composition based on measured laboratory values is presented. The model is then calibrated to reflect the actual performance of Klagshamn from 2007 denoted as the reference scenario. The composition of the AS that results from the introduction of inline hydrolysis is used with the model to assess the potential for pre-denitrification.

1 Model Presentation

The full-scale properties of Klagshamn WWTP are presented in Table 1 and were applied to the wastewater treatment simulation tool EFOR 2003.0 based on the Activated Sludge Model (ASM) 2d (Henze et al., 1999).

Name	Volume	Depth	Flow rate
AS tank	8·550 m^3	4 m	
Bottom			1000 $kgO_2 \cdot h^{-1}$
Secondary settler	8·610 m^3	3.6 m	
Return sludge (Q(RS))			1000 $m^3 \cdot h^{-1}$
Waste sludge (Q(WAS))			30 $m^3 \cdot h^{-1}$

Table 1. Analysis methods and number of measurements from the outlet of the primary settler during one operational year.

To simulate operation strategies with different wastewater characteristics (e.g., increased volatile fatty acid (VFA) concentration due to in-line primary sludge hydrolysis), the modelling framework was determined in accordance with Klagshamn's treatment steps, as presented in Figure 1.

The outlet of either the primary settler or primary sludge hydrolysis tank was used as the inlet into the AS system. In the model, the eight AS tanks in series represent eight AS zones that can be operated in either oxic or anoxic conditions (Nyberg et al., 1992).

The secondary settler's sludge separation performance based on the model of Takacs et al. (1991) was connected with the Q(RS) and Q(WAS) pump for sludge control in the AS system. For modelling reasons, the areas of the eight secondary settlers were summed up, and one secondary settler with an area of 4880 m^2 was used instead. To control the aeration in the AS tanks, Q(RS) and Q(WAS) control loops were set up, as presented in Table 2.

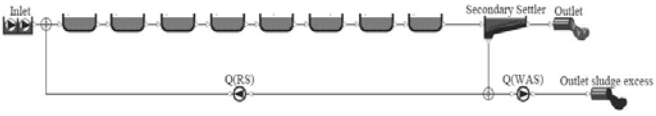

Figure 1. Layout of the AS system including the secondary settler, the return AS pump and waste AS pump in the dynamic simulation tool.

Controlled Item	Meter	Controller	Set-point	Units
Aerators AS1-8	Oxygen AS1-8	On/Off	2.5	$g \cdot m^{-3}$
Q(RS)	Time	Time	1000	$m^3 \cdot h^{-1}$
Q(WAS)	SS_{AS} in AS8	On/Off	30	$m^3 \cdot h^{-1}$

Table 2. Set-up of the control loops in the dynamic simulation tool.

1.1 Data Background

The number of analyses (n) and corresponding method of measurement at the outlet of the primary settler at Klagshamn during 2007 are shown in Table 3. The analysed compounds were suspended solids (SS), CODt, TN, ammonium nitrogen (NH_4-N), TPt, filtered phosphorus (TPs) and the sludge concentrations in the AS tank (SS_{AS}). Furthermore, the incoming wastewater flow (Q_{in}) and wastewater temperature (T_{in}) was obtained using the supervisory control and data acquisition (SCADA) system.

	Unit	Annual Measurement		Method
		n	%	
SS	$gSS \cdot m^{-3}$	82	22	SS-EN 872
CODt	$gO_2 \cdot m^{-3}$	303	83	LCK 114
TN	$gN \cdot m^{-3}$	311	85	FIA 62-04/84
NH_4-N	$gN \cdot m^{-3}$	70	19	FIA 50-02/84
TPt	$gP \cdot m^{-3}$	236	65	SS 028127-2
TPs	$gP \cdot m^{-3}$	215	59	SS 028127-2
SS_{AS}	$gSS \cdot m^{-3}$	109	30	SS-EN 872
Q_{in}	$m^3 \cdot d^{-1}$	365	100	SCADA
T_{in}	°C	365	100	SCADA

Table 3. Analysis methods and number of measurements from the outlet of the primary settler during one operational year.

2 RESULTS

2.1 Modelling Strategy

To reflect the measured data (including hydraulic variations), the model was empirically calibrated to match the actual SS measurements in the AS and the secondary settler. The wastewater treatment plant properties, process adjustments, and the wastewater treatment model that was implemented described as the reference scenario.

All data from Q_{in} were incorporated directly into the model. Two typical operational situations are shown in Figure 2. The flow is either normal ($Q_{d,\ avg} \sim 23\ 000\ m^3 \cdot d^{-1}$) or very high ($Q_{d,\ max} > 39\ 000\ m^3 \cdot d^{-1}$) due to snowmelt in the winter/spring (day 21 and 60) or heavy rainfall in the summer (day 187), respectively.

2.2 Secondary Settler

The number of layers in the flux settler (n_L) and height (m_L) were changed from $n_L = 36$ and 0.1 m_L (default) to n_L=10 and 0.36 m_L, respectively. To achieve a stable sludge concentration in the AS system while avoiding sludge loss, the default value of the non-settling fractions (f_{ns}) of 0.23% was set to zero.

Figure 2 shows the SS concentrations in the reference scenario and the actual measured values from the outlet of the secondary settler at Klagshamn during 2007.

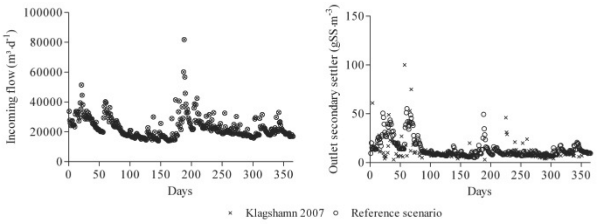

Figure 2. Q_{in} and SS from outlet secondary settler at Klagshamn WWTP during 2007. Day 0 represents Jan. 1, 2007.

2.3 Activated Sludge System

All SS measurements from the AS system at Klagshamn during 2007 were divided into ten periods with fixed set- points, as presented in Table 4. These set-points were chosen by looking at the actual SS concentrations, hich were almost constant for longer periods in the AS tank (see Figure 3).

Phase	Calendar days	Duration (days)	Klagshamn 2007 ($gSS \cdot m^{-3}$)	Set-point in EFOR ($gSS \cdot m^{-3}$)
1	001 – 022	22	2425	2400
2	023 – 082	60	2691	2800
1	001 – 022	22	2425	2400
2	023 – 082	60	2691	2800
3	083 – 124	42	2633	2400
4	125 – 141	17	3450	3500
5	142 – 169	28	3057	2900
6	170 – 225	56	2305	2200
7	226 – 270	45	2568	2700
8	271 – 292	22	2871	3000
9	293 – 309	17	2533	2700
10	310 – 365	56	2844	2900

Table 4. Mean values of SS concentration in the AS system and the SS set-points in the dynamic simulation at Klagshamn during 2007.

The actual number of zones operated under anoxic conditions (n_{DN}) in the AS system and T_{in} were included into the model presented in Figure 3. The maximal growth rate (μ_A) for the autotrophic biomass was changed from 0.9 d^{-1} (default) to 1.25 d^{-1}, and the fraction of denitrifiers in the AS system was changed from 0.6 (default) to 1.0 to calibrate the model of the AS process empirically.

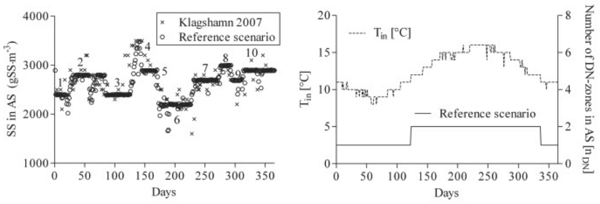

Figure 3. (left) Actual sludge concentration in the AS tank at Klagshamn during 2007 and in the reference scenario. (right) Number of anoxic zones in the AS tank in the reference scenario as a function of the inlet temperature.

2.4 Completing the Annual Composition and Variation of the Inflow Data

Extensive data were required to accurately perform an annual dynamic simulation with 24 h time steps. At Klagshamn, sampling and analyses of wastewater compounds were not performed on a daily basis, as noted in Table 3. Moreover, not all compounds were analysed simultaneously, resulting in different numbers (n) of measurements (e.g., n = 303 for CODt and n = 82 for SS, as presented in Figure 4.

To characterise the incoming wastewater and find any potential relationship between the measured compounds, a search of the literature was performed. According to Henze et al. (2002, 2008), some compounds appear in municipal wastewater in typical ratios, as presented in Table 5. Therefore, the ratio of CODt/SS, NH4-N (S_{NH4})/TN and TPs (S_{PO4})/TPt were computed to compare to literature values.

Compounds	Pairs	Ratio (raw)	R^2	Ratio (processed)	Henze et al. (2002, 2008)
CODt/SS	64	1.5	0.664	1.5	1.4 - 1.6
NH4-N/TN	61	0.7	0.878	0.7	0.6
TPs/TPt	215	0.5	0.696	0.5	0.5

Table 5. Comparison of raw and processed compound ratios from this study with literature.

Linear regression (De Veaux et al., 2008) was performed to estimate the missing values in the incomplete data set; CODt and SS estimates are presented below as examples. First, all CODt and SS concentrations measured during the same day were selected for a total of 64 pairs. Subsequently, a mean CODt/SS ratio of 1.5 was calculated and compared to the expected ratio (Table 5).

As shown in Figure 4, a scatter plot of SS (x-axis) versus CODt (y-axis) is presented to visualise the linear equation ($y = 1.2714 \cdot x + 51.355$, y = CODt, x = SS) and goodness-of-fit ($R^2 = 0.664$).

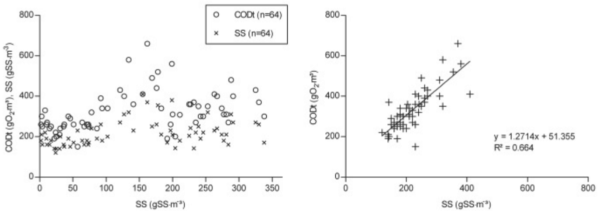

Figure 4. (left) Time series of CODt and SS pairs. (right) Scatter plot with the line of best fit.

Next, the linear equation was used to calculate the remaining CODt (n = 81) and SS (n = 237) values that were not measured on the corresponding day. A time series and a scatter plot with a line of best fit that included all calculated CODt and SS values were made (Figure 5).

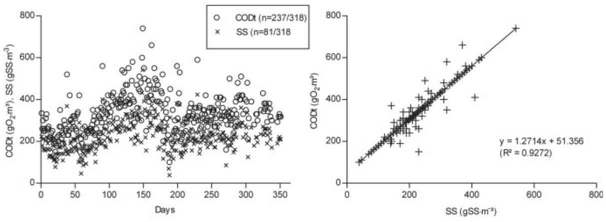

Figure 5. (left) Time series and (right) scatter plot with the best-fit line that include all calculated CODt and SS values.

On days when neither the CODt nor the SS values were measured, the annual average values (334 $gCODt \cdot m^{-3}$ and 222 $gSS \cdot m^{-3}$) from Figure 5 were used instead. Figure 6 presents a complete annual data set (n = 365) for CODt and SS values including the additional annual average values (n = 47).

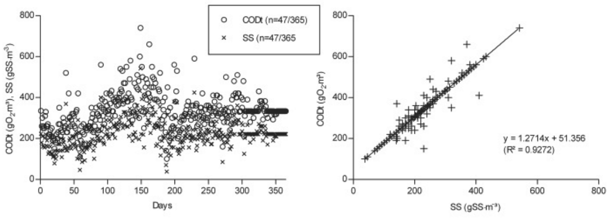

Figure 6. Complete annual data set of (left) CODt and SS values. (right) Corresponding scatter plot.

This method was used to estimate the missing data values for TPt, TPs, TN and NH_4-N.

2.5 Wastewater Characterisation

To characterise the wastewater in more detail, the *weak primary settled wastewater* was chosen as the default wastewater type based on the wastewater compounds analysed (SS, CODt, TN, NH_4-N, TPt and TPs). This setting uses predefined ratios of compounds typical of this kind of wastewater when no data are available (Henze et al., 2002).

The fraction of soluble inert COD ($f_{S,SI}$) in the total COD was calculated based on laboratory analyses using the method provided by Keskitalo et al. (2010). Therefore, the $f_{S,SI}$ was changed from 0.03 gCOD $\cdot gCOD^{-1}$ (default) to 0.12 $gCOD\cdot gCOD^{-1}$.

2.6 Implementing Sludge Hydrolysis to Characterise Incoming Wastewater

Estimates of primary sludge hydrolysis were generated for use in full-scale simulations by changing the reference scenario's wastewater characteristics. First, the VFA produced were set to increase simultaneously with the CODt and soluble COD (CODs) in the model (Henze et al., 2002, 2008; Penya-Roja et al., 2002). Therefore, the VFA was added to the CODt and CODs while the default value of the VFA (S_A) was changed.

Furthermore, any release of NH_4-N (S_{NH4}) or orthophosphate (S_{PO4}) would be added to the total nitrogen content ($C_{TN} = S_{NOX} + S_{NH4}$ + organic N) or total phosphorous ($C_{TP} = S_{PO4} + S_{p\text{-}P}$ + organic P), respectively (Henze et al., 2002).

2.7 Simulation of Sludge Hydrolysis Results for Improved Predenitrification

Hey et al. presents a full-scale in-line hydrolysis experiment at Klagshamn, and a value of 43 $gCOD_{HAc}\cdot m^{-3}$ was noted with no ammonium release. These findings were incorporated into the model and simulated with the reference scenario. The simulated results in Figure 7 show that an additional load of 40 tNO3-$N\cdot a^{-1}$ could be removed, corresponding to an annual average concentration of less than 4.7 gNO_3-N·m in the hydrolysate.

However, a load of 15 tNH_4-$N\cdot a^{-1}$ less was nitrified, corresponding to an excess of 1.6 gNH_4-$N\cdot m^{-3}$ annual average outlet concentration that is supplied to the downstream process.

Nevertheless, the simulation indicated a potential for removing a total nitrogen load of 25 $tN\cdot a^{-1}$, which corresponds to 3.1 $gN\cdot m^{-3}$ less into the downstream process.

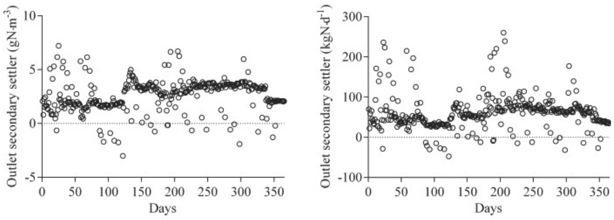

Figure 7. Simulated outlet concentrations of (left) ammonium nitrogen and (right) nitrate nitrogen from the secondary settler.

3 Discussion

Generating a complete annual data set for modelling purposes by applying linear regression was shown to produce estimates in good agreement with available data. Furthermore, the data sets agreed well with values related to typical inlet wastewater compound ratios, as reported in the literature (Henze et al., 2002, 2008). The reasonably large number of annual measurements of TN (n = 311; 85%), CODt (n = 303; 83%), TPt (n = 236; 65%) and TPs (n = 215; 59%) enabled the daily values for the more sparsely sampled NH_4-N (n = 70; 19%) and SS (n = 82; 22%) to be estimated.

The main purpose was to attain a complete data set for TN and TPt supported by experimental measurements and estimations based on the ratio of other wastewater compounds. If the wastewater compositions were incorrectly estimated, the daily load in the wastewater simulation tool would also be incorrect, resulting in false evaluation and conclusions. Almost no differences were found when the SS load from the outlet of the secondary settler between the reference scenario was compared to the actual findings from 2007 (Figure 2). This result indicates that the empirical calibration fits the data accurately.

The reference scenario was shown to be an appropriate basis for the simulation of different future scenarios. For example, the inlet wastewater characteristics could be changed to predict the potential of combining in-line hydrolysis with predenitrification to remove nitrogen in the AS process.

4 Conclusion

Dynamic wastewater treatment simulation was applied in this study and shown to be a valuable tool to quickly evaluate the potential operational changes without the risk associated with full-scale testing. Routine measurements made at most plants are not performed with the time resolution desired for modelling purposes. However, with proper treatment, less frequent measurements could be made useful. This study shows a method for estimating missing wastewater compound concentrations to obtain a complete annual data set that can be implemented in a calibrated dynamic wastewater treatment simulation tool to evaluate primary sludge hydrolysis for full-scale predenitrification.

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