Comprehensive Modelling of Full-Scale Nitrifying and Post-Denitrifying Biofilters

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ABSTRACT

In 2017, a modelling project was launched which aims to establish a whole facility model for the upgraded Seine Aval (SAV) water resource recovery facility (WRRF). For the biofiltration process, a biofiltration model found in the literature was improved and extended in terms of mass transport and biological kinetic processes. Estimations of energy consumption and greenhouse gas productions were also considered in the model. The established model has been calibrated and validated for the nitrifying and post-denitrifying biofiltration process. Simulation results showed that the calibrated model can predict treatment performance precisely. The results obtained for energy consumption and N_2O emissions during the nitrification process indicated the potential of using the model as a support tool for treatment evaluation and optimization.

Keywords: Biofiltration Modelling, Model Calibration, Greenhouse Gases, Energy Consumption

INTRODUCTION

The Seine Aval (SAV) water resource recovery facility (WRRF), the largest WRRF in France (5 million PE, Paris), is being upgraded in order to tackle todays' wastewater treatment challenges such as urbanization and water resources protection. Under this modernization programme, more intensive nutrient removal processes including membrane bioreactors (MBR) and biofilters have been applied in the plant. In 2022, chemically enhanced primary treatment (CEPT) will also be added to the plant. Without support tools such as mathematical process models, treatment performance evaluations and operation strategy developments will be complicated for the plant with large-scale use of intensive processes. Therefore, in parallel with the upgrade of the Seine Aval WRRF, SIAAP (the interdepartmental association for sewage disposal in the Paris agglomeration) launched the NEXTSTEP project with the goal of developing a whole plant model for the SAV facility. Currently, models for the nitrifying biofilter and post-denitrifying biofilter process as well as the CEPT process have been successfully established. The modelling works for the pre-denitrifying process and the MBR process are still underway. The objective of this contribution is to share the methodology and results of the biofiltration process modelling work and to show the potential application of the model for treatment optimization.

METHODOLOGY

A biofiltration model based on Bernier et al. (2014) has been implemented in WEST® (Version 2016, DHI, Hørsholm, Denmark). The original model was mainly improved in the following ways: Firstly, for mass transport, diffusion of soluble components between bulk liquid and biofilm is limited by a boundary layer with variable rather than constant thickness. In addition, the number of biofilm layers has been expanded from two to five in order to more precisely describe the concentration gradients in the biofilm. Secondly, because of the interest in N_2O

emission evaluation, a simplified gas phase as well as multi-step biological reactions for nitrification and denitrification have been applied (Pocquet et al., 2016; Hiatt and Grady, 2008). Finally, energy consumption estimations for aeration and pumping have been integrated in the model. By using the Monte Carlo based approach of Sin et al. (2008), the model was first calibrated using data of the nitrification stage (84 Biostyr® biofilters, 6 treatment units) over a short period before the upgrade (from mid-July to mid-August 2009). To increase model accuracy, the identified parameter values were then adjusted manually according to simulation tests over short and long periods of the year 2009. Final validation of the model has been realized with long period datasets collected after the upgrade of the biofiltration stage (from mid-April to mid-October 2017). The model was then applied for the post-denitrification process with a similar calibration procedure. Since there were several treatment issues in the post-denitrification stage at the start-up of the upgraded SAV WRRF, calibration of the post-denitrifying model was realized for the process in the Seine Centre (SEC) WRRF which uses the same type of biofilter (12 Biofor® biofilters, 3 treatment units). In rain weather, the treatment configuration of this stage can be turned into COD elimination with aeration. The calibration of this stage focused on the post-denitrifying configuration and was realized for one treatment unit with datasets collected in 2008 (from October to mid-November). The calibrated model was then validated for the entire stage with datasets collected from April to mid-September of the same year.

RESULTS

Results for the Nitrification Stage

Simulation results for the effluent ammonium concentrations of the nitrification stage between mid-August to mid-October of year 2017 (validation period) are shown in Figure 1. Statistical scores which indicate model prediction accuracy for the nitrification stage are summarized in Table 1. Estimations of daily energy consumption during nitrification treatment in the validation period are compared with the real consumption data in the stage and shown in Figure 2. The average emission factors (EF %) for N_2O obtained in the nitrification stage for the calibration and validation period are 5.3% and 6.2% respectively. The emission factor obtained in the winter period of the year 2009 was 5.9% (60 days) which was higher than the value obtained in the summer period (2.9%, 60 days).

Table 1 Statistical score results for the nitrification stage model performance.

Scores for calibration period	NH_4^+	NO_x	DO	NO_3^-	NO_2^-	COD	TSS	PO_4^{3-}
Number of validated observations	27048	34272	33313	327	329	331	332	329
Observed mean (mg/L)	5.55	34.04	6.63	33.29	0.78	62.27	21.58	0.39
Mean error (mg/L)	-0.32	2.84	-0.22	2.80	-0.13	2.99	3.88	0.07
Root mean square error (mg/L)	3.57	4.88	0.79	4.60	0.56	15.08	11.83	0.16
Scores for validation period	**NH_4^+**	**NO_x**	**DO**	**NO_3^-**	**NO_2^-**	**COD**	**TSS**	**PO_4^{3-}**
Number of validated observations	14841	14841	17226	177	178	180	180	180
Observed mean (mg/L)	2.30	19.12	6.40	18.67	0.77	41.52	10.68	0.76
Mean error (mg/L)	-0.32	2.27	-0.89	2.41	0.17	-0.31	-0.31	-0.12
Root mean square error (mg/L)	1.53	3.53	1.27	2.98	0.79	5.37	3.39	0.17

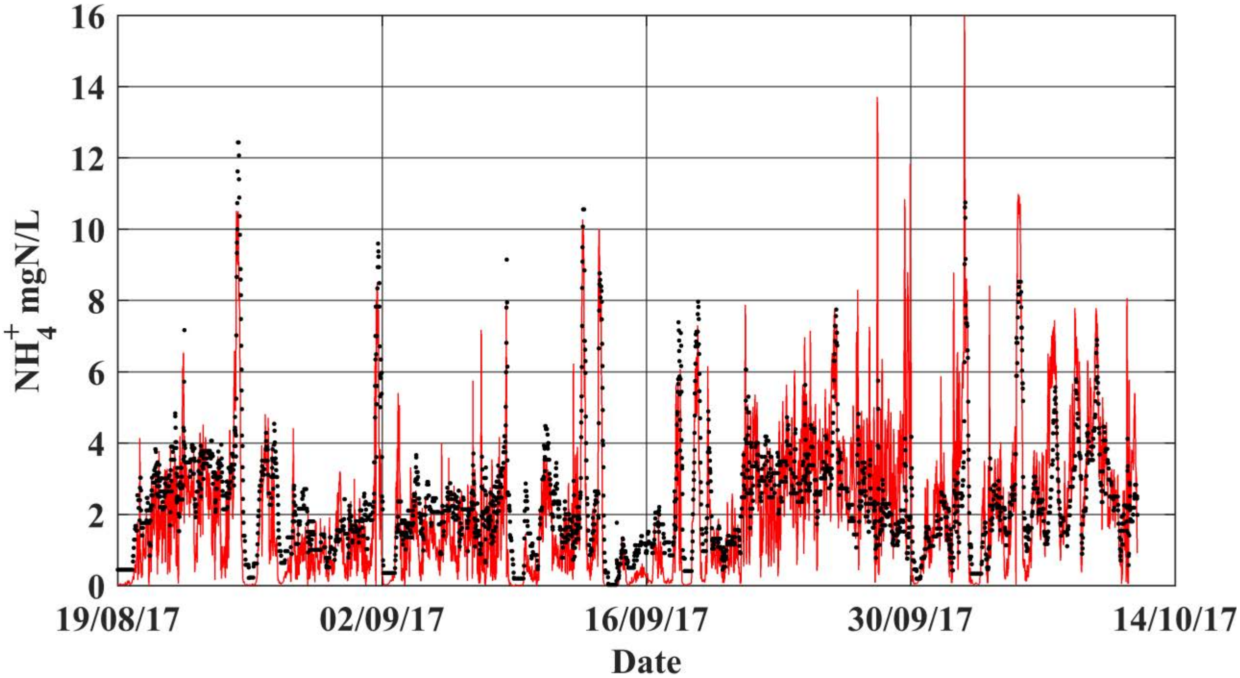

Figure 1 Validation simulation results (red line) and observations (black dots) for the effluent NH_4^+ concentrations of the nitrification stage in the SAV WRRF.

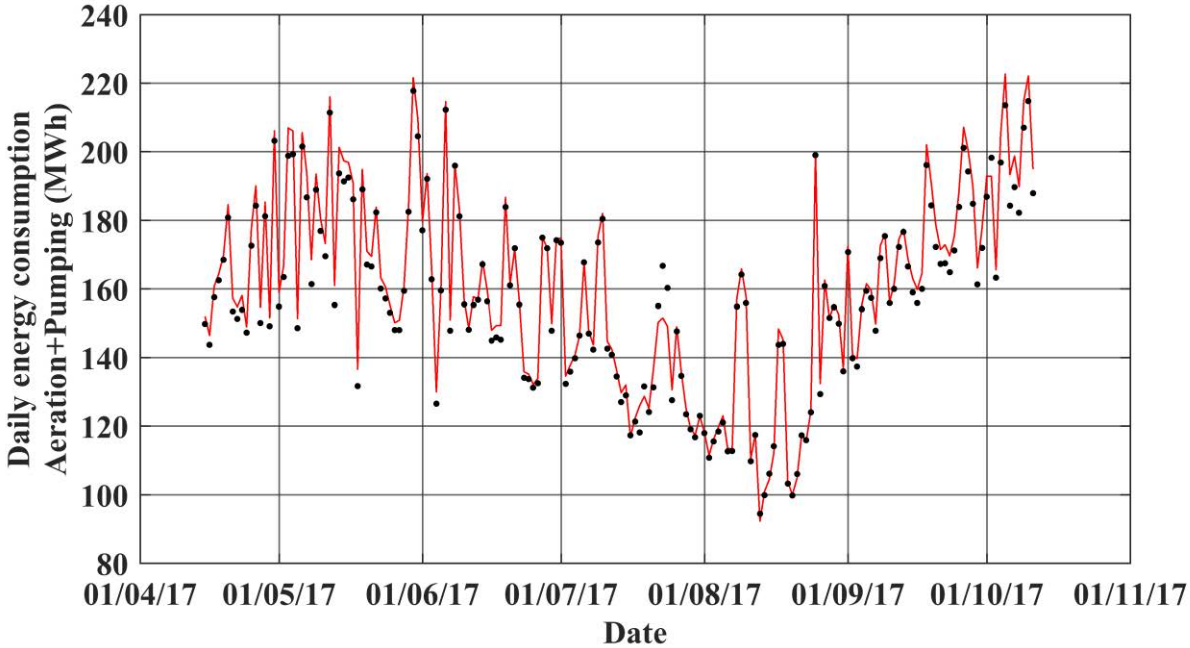

Figure 2 Estimations of the energy consumption (sum of aeration and pumping) for the nitrification stage in the SAV WRRF (Red line: Simulation, Black dots: Observations)

Results for the Post-Denitrification Stage

For the post-denitrification stage, Table 2 summarizes the statistical scores calculated for the simulation results obtained for calibration and validation. Figure 3a and b show the simulated effluent NO_x concentrations in the validation period and their comparisons with the laboratory daily monitoring data (sum of NO_2^- and NO_3^-) and on-line sensor data.

Table 2 Statistical score results for the post-denitrification stage simulation

Scores for calibration period	**[1]NO_x**	**NH_4^+**	**COD**	**CODs**	**TSS**	**PO_4^{3-}**
Number of validated observations	1906	50	50	35	35	50
Observed mean (mg/L)	3.67	1.12	26.52	22.48	4.68	0.28
Mean error (mg/L)	1.11	0.65	-0.82	-0.01	-1.80	0.04
Root mean square error (mg/L)	2.32	1.27	4.31	3.17	3.10	0.12
Scores for validation period	**[1]NO_x**	**NH_4^+**	**COD**	**CODs**	**TSS**	**PO_4^{3-}**
Number of validated observations	3704	162	162	109	109	162
Observed mean (mg/L)	4.03	1.29	28.94	23.97	5.56	0.25
Mean error (mg/L)	0.50	0.39	-1.56	-1.67	-1.61	0.11
Root mean square error (mg/L)	1.79	1.30	6.00	4.57	3.77	0.18

[1]Sensor data collected under post-denitrifying configuration

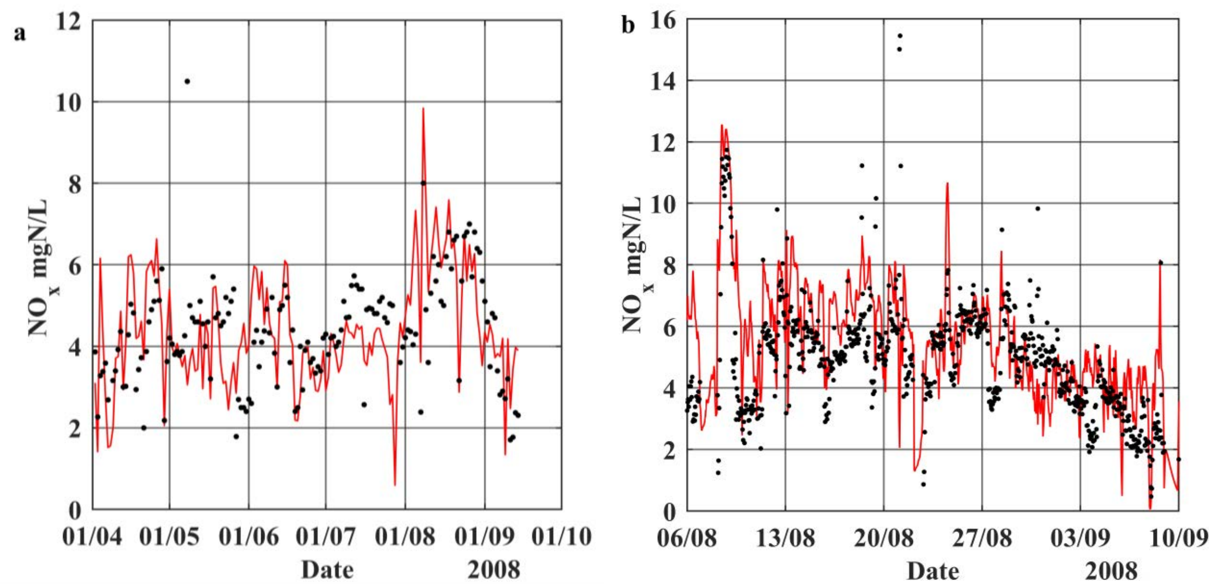

Figure 3 Validation simulation results (red line) and observations (black dots) for the effluent NO_x concentrations of the post-denitrification stage in the SEC WRRF. a. Daily average results (Observations: Laboratory). b. Hourly average results (Observations: NO_x sensor data).

DISCUSSION

For the nitrification stage, the general variations of effluent NH_4^+ concentrations are well followed by the model (Figure 1). The low mean error (ME) values (-0.32 mgN/L) obtained in the calibration and validation periods also confirm the good model prediction performance. The model prediction accuracy for effluent TSS and COD concentrations was better in the calibration period, which was partially related to the availability of measurements of the influent soluble COD and the treatment configuration change in 2017 in the facility. These allowed to improve fractionation and made the influent TSS concentrations more accurate. The good estimations obtained for daily energy consumption can facilitate further treatment cost and environmental impacts assessment. The simulated N_2O emission factors were higher than the values (2.26% in summer and 4.86% in winter) observed for the nitrifying biofilter process (Bollon et al., 2016). However, the seasonal difference in N_2O emissions reported in the study was also predicted by the model. It should be noted that the effluent nitrite concentrations observed in the simulated periods were higher than the periods studied by Bollon et al. (2016), which may have increased the simulated N_2O production.

For the post-denitrification stage, the general variations of the effluent NO_x concentrations in the stage were well predicted by the model (Figure 3a). Compared with the sensor data, only a few prediction failures were observed (Figure 3b) which may be related to the operational differences between the treatment units. The statistical scores (Table 2) show that the effluent CODs concentrations were accurately predicted. The effluent ammonium concentrations were overestimated, which may be related to the underestimation of the slight nitrification that occurred when the treatment configuration of the stage turned into aerobic COD removal.

CONCLUSIONS

The biofiltration model that was developed and improved is able to accurately predict the treatment performance for both nitrifying and post-denitrifying biofilter processes. The results showed the potential of the model to be used as a support tool to evaluate treatment costs and environmental impacts. With the accomplishment of the modelling works for the other treatment processes in the Seine Aval facility, an integrated plant model can be established and applied for the development of optimization strategies for the modernised facility.

ACKNOWLEDGEMENTS

The authors would like to thank the MOdelling, Control and Optimisation of wastewater treatment processes program (MOCOPEE) for financially supporting this work. Peter Vanrolleghem holds the Canada Research Chair on Water Quality Modelling.

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