Enhanced nutrient removal MBR system with chemical addition for low effluent TP

Wen-jun Liu, Zhi-rong Hu, R. L. Walker and P. L. Dold

ABSTRACT

A pilot study was conducted to test an membrane bioreactor (MBR) process for combined biological and chemical P removal to achieve a very low effluent total phosphorus (TP) concentration of 0.025 mg P/L. With the data from the pilot test, a simulation study was performed to demonstrate that: (1) the pilot system behaviour (effluent quality, MLSS, etc.) can be modelled accurately with an activated sludge model combined with a chemical precipitation model; and (2) with the calibrated model, simulation scenarios can be performed to further understand the pilot MBR process, and provide information for optimizing design and operation when applied at full-scale. Results from the pilot test indicated that the system could achieve very low effluent TP concentration through biological P removal with a limited chemical addition, and chemical addition to remove P to very low level did not affect other biological processes, i.e., organic and nitrogen removal. Simulation studies indicate that the process behaviour can be modelled accurately with an activated sludge model combined with a chemical precipitation model, and the calibrated model can be used to provide information to optimize system design and operation, e.g., chemical addition control under dynamic loading conditions is important for maintaining biological P removal.

Key words | MBR, nutrient removal, chemical addition, pilot plant modelling, simulation low effluent TP limit

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INTRODUCTION

To meet the need of water reuse and control eutrophication to protect the receiving water quality, more stringent nutrient (total nitrogen-TN and total phosphorus-TP) effluent limits from municipal wastewater treatment plants are becoming popular (e.g. Lesjean *et al.* 2003; Phagoo *et al.* 2005; Barnard & Stelchen 2006; Oleszkiewicz & Barnard 2006). In many parts of North America, very stringent effluent TP limits (0.03–0.10 mg P/L) are required (Phagoo *et al.* 2005). An example is the City of Siloam Springs, Arkansas, which must meet an effluent TP limit of 0.025 mg P/L.

Achieving these limits demands very low soluble P, and essentially a solids-free effluent. Nutrient removal activated sludge systems incorporating membrane bioreactors (MBRs) which are able to produce solids-free effluent are becoming an attractive technology. In a conventional biological nutrient removal activated sludge systems with settling tanks, say the effluent TSS is 10 mg/L, the P content of the solids, will contribute approximately 0.3 mg P/L to the effluent (Dold *et al.* 2009). Biological nutrient removal in MBRs (BNR MBR) has been successfully achieved at lab scale and full scale and the design procedure and considerations for these systems have been proposed (e.g. Adam *et al.* 2002; Lesjean *et al.* 2003; Daigger & Crawford 2005; Phagoo *et al.* 2005; Ramphao *et al.* 2003, 2006; Monti *et al.* 2007; Dold *et al.* 2009). Achieving very low soluble P concentrations through biological P removal depends on having favourable influent wastewater characteristics, and may not be feasible. In those cases biological P removal can be supplemented with limited addition of chemicals for precipitation of P, i.e., to utilize a biological N and P removal configuration to achieve the maximum possible amount of biological P removal and add a limited amount of chemicals (ferric or alum, typically) to the process to 'touch up' and meet the very low TP limit. One example of this approach is at the Cauley Creek plant which consistently achieves an effluent TP of less than 0.1 mg P/L, ammonia less than 0.2 mg N/L, and TN of 4–5 mg N/L (Phagoo *et al.* 2005).

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However, chemical precipitation of soluble phosphate to very low concentrations may inhibit biological P removal and even other biological activities such as nitrification and denitrification because of the shortage of phosphorus as a necessary nutrient. To investigate the effect of chemical addition on the performance of the enhanced nutrient removal (ENR) MBR systems, a pilot scale study and process modelling were conducted. The objectives of this paper are to report on (1) a pilot plant study to test and demonstrate an ENR MBR process with limited chemical addition to achieve a very low effluent TP concentration; (2) a simulation study to demonstrate that the behaviour of the pilot plant system (effluent quality, MLSS, etc.) can be modelled accurately with an activated sludge model combined with a chemical precipitation model, and (3) application of the calibrated model to various simulation scenarios to further understand the pilot MBR process performance and provide information for optimizing design and operation of the full-scale MBR application.

MATERIALS AND METHODS

Pilot plant study

Description of the pilot ENR MBR system

The existing wastewater treatment plant in the city of Siloam Springs, Arkansas discharges to the scenic Illinois River in Northeast Oklahoma. The plant needs to be upgraded to meet a very stringent TP limit of 0.025 mg/L. An ENR MBR system (Figure 1), developed by Siemens Water Technology was considered as a candidate process to achieve the target TP limit. Siemens Water Technology was retained by the City and Garver Engineers to pilot test its system on primary effluent at the WWTP. The process configuration is a UCT type BNR system with a membrane tank to replace the setting tank for solid liquid separation (see Figure 1). A unique feature for this ENR MBR system is a small contact tank (10 min HRT) for chemical dosing, located between the main aerobic reactor and membrane tank. Objectives of the pilot study included evaluating (1) the possible impact of a low phosphate concentration on biological activity in the main bioreactor and (2) the potential impact of chemical addition on membrane fouling. The membrane tank hosted PVDF hollow fibre membranes with normal pore size of 0.04 mm and maximum pore size 0.1 mm.

Design, operation and monitoring of the pilot plant

The design and operation parameters for the pilot plant system are listed in Table 1. The pilot plant process was operated from 9 December 2005 to 9 May 2006 which is divided into four phases: start-up, optimization, demonstration and recovery. The system SRT was 51 days. The long SRT was utilized to completely mineralize soluble organic P to be removed by chemical precipitation.

The membrane operating system (MOS) was operated in the following way: a filtrate flow rate of 900 L/h, a flux of 24 L/(m^2 h), relaxation interval of 12 min, relaxation duration of 1 min (increased to 1.5 around 24 March 2006), membrane aeration in an air flow rate of 9 m^3/h maintenance clean by 500 ppm chlorine, weekly and citric acid plus variable HCL.

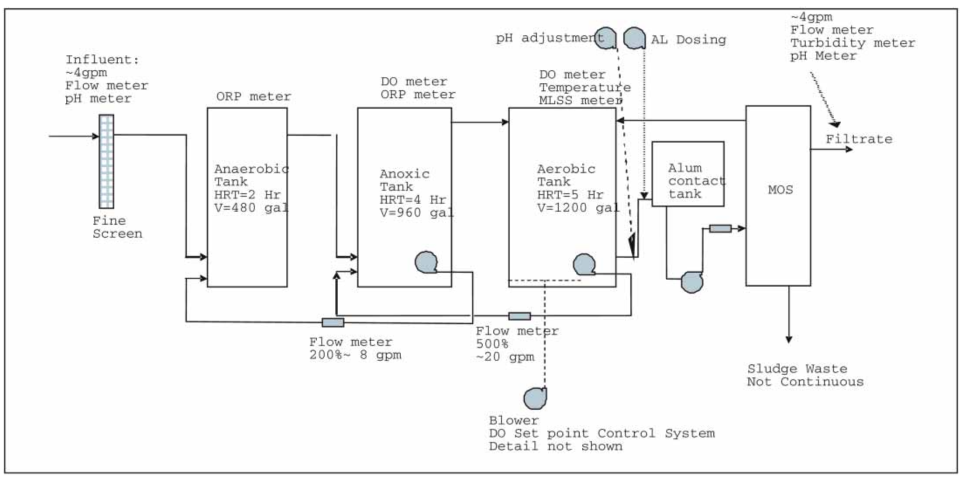

Figure 1 | MBR pilot plant configuration.

Table 1 | Design and operating parameters for the pilot process (Siloam Springs)

Reactors	Volume (L)	Operation	Values (units)
Anaerobic (AN)	1,816.8	Flow rate	21,802 (L/day)
Anoxic (ANO)	3,633.6	SRT	51 (day)
Aerobic (AE)	4,542	Dissolved oxygen (DO)	2 in AE and 7 in MOS (mg O/L)
Alum contact tank	3,78.5	Alum dosing	17.5 mg/L influent flow
Membrane tank (MOS)	2,65.7	Temperature	Approximately 20 °C

(1) Recycle ratios with respect to influent flow (100%): 200 from ANO to AN; 500 from AE to ANO; 400 from MOS to AE.
(2) Sludge waste – manually initiated, weekly maintain MLSS in aerobic zone between 9,000 and 10,000 mg/L.

The pilot system was monitored from 30 December 2005 to 20 April 2006. During the monitoring period, MBR influent and effluent samples were collected using 24 h composite samplers. Mixed liquor samples in the aerobic bioreactor were 6 h composite samples. These samples were sent to a local certified lab for analysis. TP was measured using EAP method 365.5 and other parameters were analyzed using Standard Methods (APHA/AWWA/WEF 1985).

Simulation study

Process model used for simulation

The process model used in this paper is the full general activated sludge/anaerobic digestion model implemented in BioWin™ (EnviroSim 2008). This integrated model includes activated sludge and anaerobic digestion environments, as well as modelling of pH, gas transfer and chemical precipitation. The model tracks over 50 components, with more than 80 processes acting on these components, and has been applied extensively for modelling the large number of processes occurring in complex ENR systems.

Model calibration for the pilot plant system

The stepwise procedure outlined in the WERF manual (Melcer *et al.* 2003) was followed to calibrate the pilot plant model. The pilot plant model configuration set up in BioWin is shown in Figure 2. Data obtained from the pilot test study during the monitoring period from 30 December 2005 to 20 April 2006 were used for model calibration.

The design and operation parameter values shown in Table 1 were applied for the physical and operation parameters. The average influent input parameter values (primary effluent from the existing plant) and wastewater characteristic parameters are listed in Table 2. It should be noted that values of influent daily input parameter applied in the calibration were obtained from the measured daily results during the long-term operation (see Figure 3, top for COD, middle for TKN and bottom for TP), but the wastewater characteristic parameter (fractions) values were kept unchanged. A significant factor in terms of biological P removal was the unusually high nitrate concentration (approx. 5 mg N/L) in the influent. Default values for the kinetic and stoichiometric parameters in BioWin™ (EnviroSim 2008) were used in all simulations in either model calibration or model application except for the maximum growth rate of nitrifiers which was calibrated against the measured system effluent ammonia concentration.

Application of the calibrated pilot plant model

After calibrated, the pilot plant MBR model can be used to perform various simulation scenarios to investigate

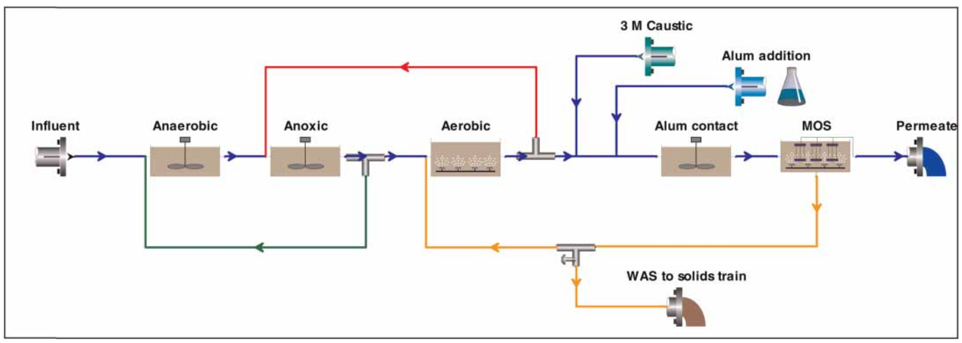

Figure 2 | MBR pilot plant model configuration implemented in BioWin simulator.

Table 2 | Influent input parameter values for the pilot plant model

Average influent input (units)	Values	Wastewater fractions (units)	Values
Flow rate (m^3/day)	22	Fbs: RBCOD (including acetate) [gCOD/g of total COD]	0.270
Total COD (mg COD/L)	327	Fac: Acetate [gCOD/g of readily biodegradable COD]	0.150
VSS (mg VSS/L)	109	Fxsp: Non-colloidal SBCOD [gCOD/g of slowly degradable COD]	0.500
TSS (mg TSS/L)	84	Fus: Unbiodegradable soluble [gCOD/g of total COD]	0.038
Total TKN (mg N/L)	37	Fup: Unbiodegradable particulate [gCOD/g of total COD]	0.080
Total P (mg P/L)	5.3	Fna: Ammonia [gNH3-N/gTKN]	0.61
Nitrate N (mg N/L)	4.9	Fnox: Particulate organic nitrogen [gN/g Organic N]	0.250
pH	7.2	Fnus: Soluble unbiodegradable TKN [gN/gTKN]	0.020
Alkalinity (mmol/L)	3	FupN: N: COD ratio for unbiodegradable part. COD [gN/gCOD]	0.035
Calcium (mg/L)	160	Fpo4: Phosphate of TP [gPO4-P/gTP]	0.750
Magnesium (mg/L)	20	FupP: P:COD ratio for unbiodegradable part. COD [gP/gCOD]	0.011

the pilot tested MBR process for further understanding the system and providing information which may not be obtained from the pilot study for optimizing design and operation when applied in full-scale. In this study, two simulation scenarios were conducted to investigate (1) the impact of chemical addition on the process performance by comparing simulation results with and without chemical addition, and (2) the impact on process performance of operating parameters, e.g., a change in the recycle ratio from aerobic to anoxic reactor.

RESULTS AND DISCUSSIONS

Pilot test study

To evaluate the pilot plant performance, measured daily results are plotted for the effluent COD and nitrate concentrations (Figure 4), and for the effluent ammonia and TP concentrations (Figure 5) during the monitoring period (from 30 December 2005 to 20 April 2006):

- The measured COD results indicate that the pilot plant COD removal was very good, with an average effluent COD of 12.7 mg/L for whole monitoring period and 17.9 mg/L during the demonstration phase from 6 March 2006 to 14 April 2006.
- The measured effluent NH_3-N concentrations show that the pilot test MBR system nitrified completely, with an average NH_3-N of 0.61 mg/L during the whole monitoring period and 0.045 mg/L during the demonstration period. Measured average effluent NO_3-N was 6.1 mg/L for the whole monitoring period and 6.2 mg/L during the demonstration phase. The effluent nitrogen permit limit for this project was ammonia + nitrate: monthly average < 8.0 mg/L and weekly average: 10.0 mg/L. The results indicate that the requirement was met.
- Measured effluent TP results are plotted in Figure 5 and show that the system exhibited a biological P removal, but performance varied significantly before chemical addition commenced on 20 January 2006 (this will be discussed in simulation study late). With chemical addition, the effluent average TP concentration was 0.032 mg P/L during the demonstration period. This includes one daily value of 0.256 mg/L on the day when the membranes were cleaned in place because the pilot only had a single membrane tank. If this value is excluded, the average effluent TP concentration would be 0.024 mg P/L during the demonstration phase, lower than monthly average 0.025 mg/L requirement.

The pilot test results indicate that the MBR process is able to achieve the extremely low TP permit limit and chemical addition does not affect other biological activities, i.e., COD removal, nitrification and denitrification. However, simulation results for the calibration period indicate that the chemical addition may have been excessive, and negatively impacted biological phosphorus removal. Apparently the growth of PAOs was limited because insufficient phosphate was available for polyphosphate accumulation

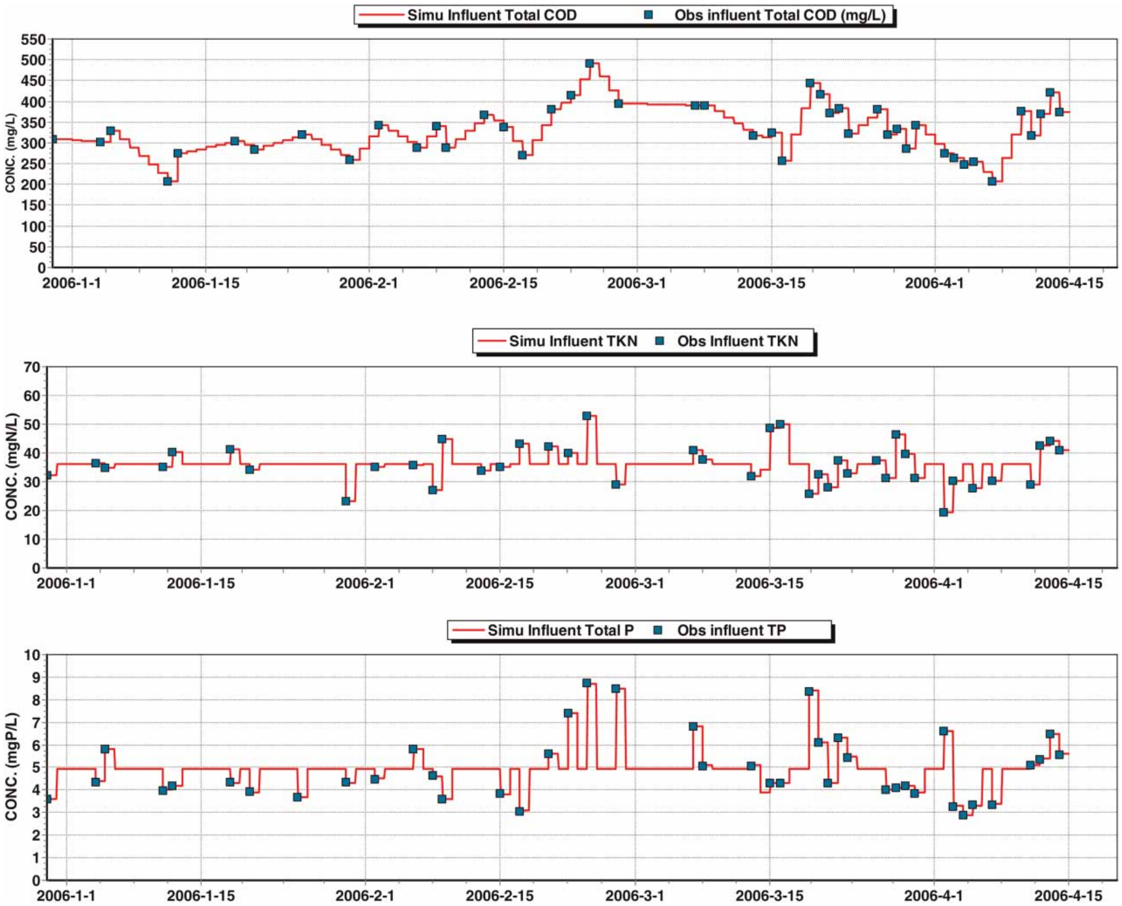

Figure 3 | Influent COD, TKN and TP input for long-term dynamic calibration.

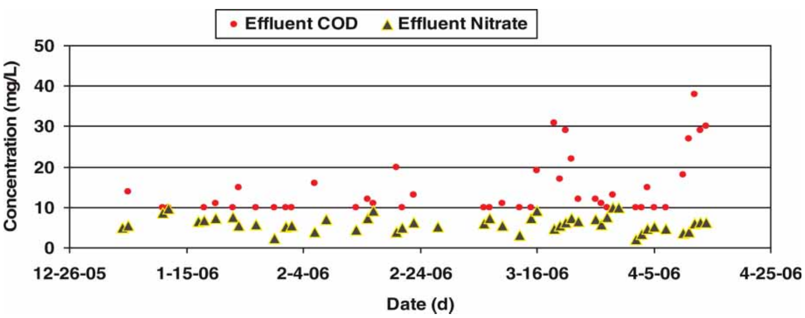

Figure 4 | Effluent NO_3-N and COD concentrations during the monitoring period.

in the aerobic bioreactor. This aspect is investigated in the simulation study later.

Calibration of the pilot plant model

To calibrate the pilot plant model, the whole monitoring period from 30 December 2005 to 14 April 2006 was simulated by running a dynamic simulation of plant performance subject to the varying daily primary effluent flows and concentrations (e.g. COD, TP, TKN, nitrate, pH, alkalinity, and ISS, process temperature, WAS flows and chemical addition flows. Default values for kinetic and stoichiometric parameters in the activated sludge model and pH and chemical precipitation models were applied. One

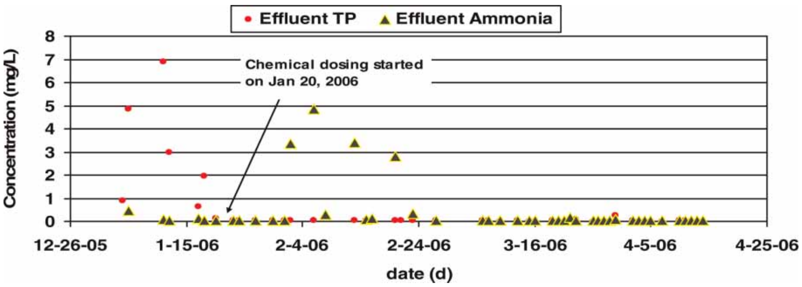

Figure 5 | Effluent TP and NH_3-N concentrations during the monitoring period.

exception for the kinetic parameters was the maximum ammonia oxidizing nitrifier growth rate which was changed from the default value of 0.9/day –0.7/day at 20 °C by calibration against system effluent ammonia concentration. Simulated and measured results are shown in Figure 6 for TSS concentration in aerobic reactor and effluent COD concentration and Figure 7 for effluent ammonia, nitrate and TP concentrations.

It can be seen from Figures 6 and 7 that:

- The model accurately tracks the pilot MBR system sludge production and effluent COD concentration under both biological and chemical precipitation conditions;
- The model was able to reasonably predict nitrification, denitrification and both biological and chemical P removal performance in the pilot MBR system.

It should be noted that measured effluent ammonia concentrations were significantly higher than predicted from 2 February 2006 to 20 February 2006. This can easily be corrected by adjusting nitrification kinetic parameters. However, the information was not available to justify making this adjustment and also the purpose of the calibration was not to force a good fit to the data by making parameter adjustments, but rather to demonstrate that the model can predict the general performance reasonably. Simulation results also showed that biological P removal occurred before chemical was added to the system, but the significant variation in bioP removal performance reflected the variation of the nitrate load to the anoxic reactor, and nitrate recycled to the anaerobic reactor (in addition to nitrate from the influent). Denitrification by OHOs in the anaerobic zone reduced the amount of RBCOD available for PAOs (see Figure 8).

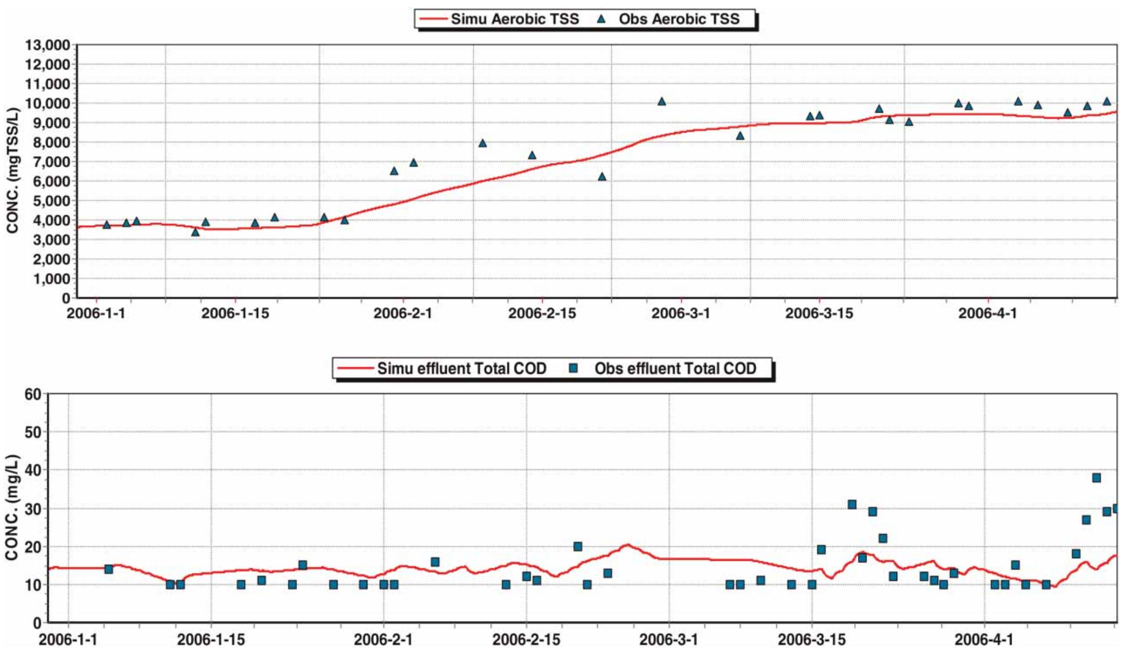

Figure 6 | Simulated (Simu) and observed (Obs) TSS concentrations in aerobic tank (top) and effluent COD concentrations (bottom).

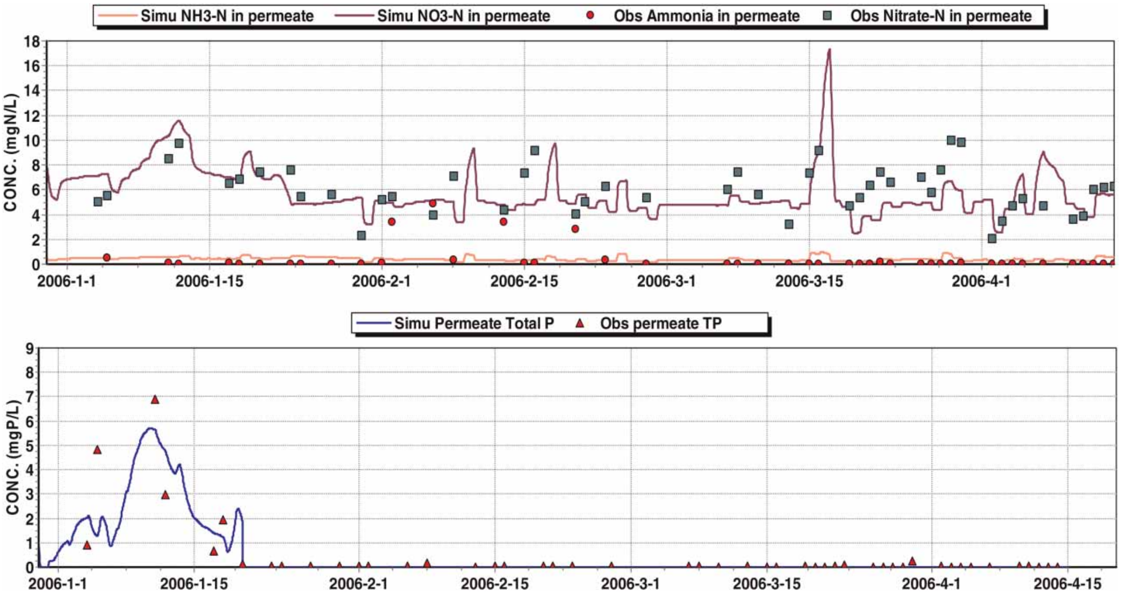

Figure 7 | Simulated and observed effluent NH_3-N/NO_3–N (top) and TP (bottom) concentrations.

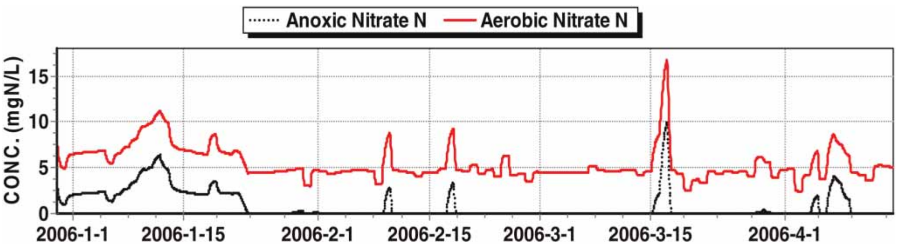

Figure 8 | Simulated nitrate concentration in anoxic and aerobic reactors.

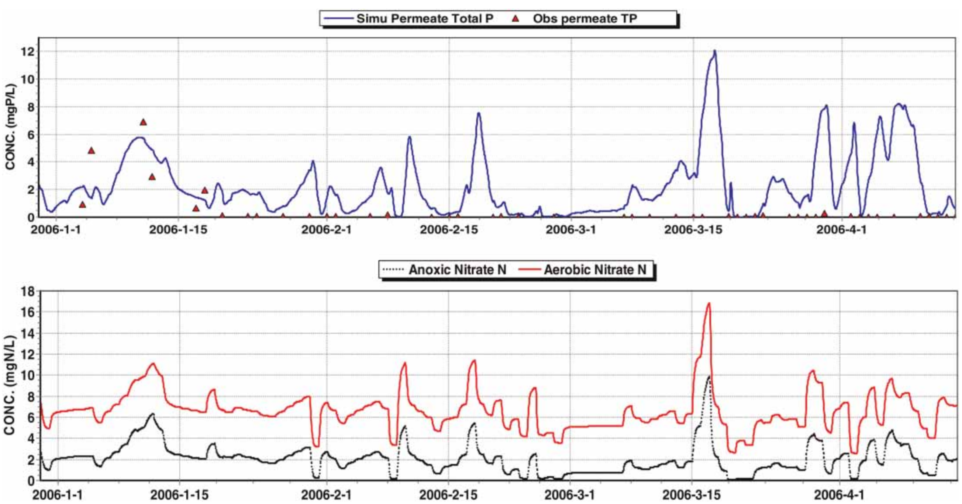

Figure 9 | Simulated effluent TP (top) and anoxic and aerobic nitrate concentrations (bottom) with the calibrated pilot plant model, but without chemical addition.

Application of the calibrated pilot plant model

With the calibrated pilot plant MBR model, various simulation scenarios were conducted to investigate the pilot-tested MBR process to provide further understanding of system performance and a basis to optimize N and P removal in the system; e.g., by changing the recycle ratio from the aerobic to anoxic zone. Space limitations preclude an extensive presentation of results, and only one simulation scenario is presented as an example to demonstrate application of the calibrated MBR model; the impact of chemical addition on process performance. This was achieved through running simulations with the calibrated model, but without chemical addition, and comparing simulation results to the case with chemical addition.

Simulation results for effluent TP concentrations and nitrate concentrations in the anoxic and aerobic reactors are shown in Figure 9 with the calibrated pilot MBR model, but without chemical addition. Results indicate that the MBR system is able to remove phosphorus biologically, but performance is affected significantly by nitrate recycled from the anoxic reactor to the anaerobic reactor (adding to the nitrate load on the anaerobic reactor from the influent). Also, comparing the anoxic nitrate concentrations without chemical addition (Figure 9) to those with chemical addition (Figure 8), it appears that excessive chemical addition inhibited bioP removal as anoxic nitrate concentrations are significantly lower with than without chemical addition. This impacts the amount of RBCOD available for PAOs.

CONCLUSIONS

The pilot test results demonstrated that the BNR MBR process is able to achieve extremely low effluent TP concentrations through combined biological and chemical P removal. Chemical addition does not affect other biological activities, i.e., COD removal, nitrification and denitrification. Data available for model calibration were limited; nevertheless pilot plant performance (sludge production, effluent quality) was predicted very reasonably based on default model parameters (with a minor adjustment to AOB growth rate).

The calibrated model provides a useful tool for identifying and investigating factors that impact plant performance, and a basis for optimizing full-scale plant design and operating mode; for example:

- Nitrate in the primary effluent (from sidestream solids handling at the plant) has a negative impact on biological P removal through reducing RBCOD availability for PAOs.
- Overloading the anoxic reactor with nitrate, with resulting recycle of nitrate to the anaerobic zone, exacerbates the problem.
- In these combined biological/chemical P removal systems care should be taken not to overdose chemicals, and controlled addition of chemical should be applied under dynamic loading conditions to avoid upsetting biological P removal. Adding excess chemical reduces phosphate concentration in the aerobic zones; if no phosphate is available for uptake by PAOs, growth of these organisms will be constrained, and the benefits of biological removal will be lost.

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