Model-based evaluation of mechanisms and benefits of mainstream shortcut nitrogen removal processes

Ahmed Al-Omari, Bernhard Wett, Ingmar Nopens, Haydee De Clippeleir, Mofei Han, Pusker Regmi, Charles Bott and Sudhir Murthy

ABSTRACT

The main challenge in implementing shortcut nitrogen removal processes for mainstream wastewater treatment is the out-selection of nitrite oxidizing bacteria (NOB) to limit nitrate production. A model-based approach was utilized to simulate the impact of individual features of process control strategies to achieve NO_2^--N shunt via NOB out-selection. Simulations were conducted using a two-step nitrogen removal model from the literature. Nitrogen shortcut removal processes from two case studies were modeled to illustrate the contribution of NOB out-selection mechanisms. The paper highlights a comparison between two control schemes; one was based on online measured ammonia and the other was based on a target ratio of 1 for ammonia vs. NOx (nitrate + nitrite) (AVN). Results indicated that the AVN controller possesses unique features to nitrify only that amount of nitrogen that can be denitrified, which promotes better management of incoming organics and bicarbonate for a more efficient NOB out-selection. Finally, the model was used in a scenario analysis, simulating hypothetical optimized performance of the pilot process. An estimated potential saving of 60% in carbon addition for nitrogen removal by implementing full-scale mainstream deammonification was predicted.

Key words | anammox, ammonia oxidizing bacteria (AOB) seeding, mainstream deammonification, NO_2^--N shunt, NOB out-selection, online control, transient anoxia

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INTRODUCTION

Shortcut processes involve the creation of unique conditions to steer the biological conversion of oxidizable nitrogen (i.e. NH_4^+-N and organic nitrogen) to nitrogen gas by taking a two-step pathway shortcut and thus conserve energy. There are two main shortcut nitrogen removal processes, i.e. nitritation/denitritation and deammonification via anammox. In both processes, the first step of the nitrogen shortcut pathway is converting NH_4^+-N via ammonia oxidizing bacteria (AOB) to NO_2^--N only. This requires repressing the nitrite oxidizing bacteria (NOB) population to avoid producing NO_3^--N. The second step can either be converting NO_2^--N to N_2 gas via heterotrophic bacteria using organic carbon or via anammox bacteria without the need for organic carbon. While the operational strategies are well documented for sidestream applications (van de Graaf *et al*. 1996; Hellinga *et al*. 1998; Gut *et al*. 2005; van Loosdrecht & Salem 2005; Wett 2007), many recent studies were conducted to address these challenges for mainstream applications using nitritation/denitritation (Peng *et al*. 2004, 2012; Blackburne *et al*. 2008; Gao *et al*. 2009, 2014; Regmi *et al*. 2013) and deammonification (Winkler *et al*. 2011; Al-Omari *et al*. 2013; Hu *et al*. 2013; Wett *et al*. 2013) or both

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(Vlaeminck *et al.* 2012; Stinson *et al.* 2013). Several approaches which rely on a kinetic-based NOB out-selection mechanism were identified where AOB, anammox and ordinary heterotrophs (OHO) can outcompete NOB for substrate. These approaches include (1) operating at low dissolved oxygen (DO) concentration, (2) operating at high DO concentration, (3) operating with high residual ammonia, and (4) transient anoxia (alternating between oxic and anoxic conditions). In the context of controlling the nitrogen process toward out-selection of NOB, intermittent aeration provides a means to control the aerobic solids retention time (SRT), as well as to introduce a lag time for NOB to transition from the anoxic to aerobic environment, either due to NO_2^--N limitation (Knowles *et al.* 1965; Chandran & Smets 2000) or by an enzymatic lag (Kornaros & Dokianakis 2010). Aggressive SRT, near minimum SRT, is applied based on target removal rates and is controlled via manipulating wasting rates, aerobic volumes and DO set-points to maximize NOB out-selection potential (Regmi *et al.* 2013; Wett *et al.* 2013). The purpose of this study was to use a mathematical model to simulate and evaluate the impact of individual features of process control strategies and process configuration to achieve nitrite shunt via NOB out-selection. Two case studies that utilize two control strategies for NOB out-selection were selected to compare to the model used in this modeling study; one study employing an ammonia vs. NOx (AVN) controller in a nitritation/denitritation pilot (Regmi *et al.* 2014) and the other employing ammonia-based control for a mainstream deammonification pilot (Al-Omari *et al.* 2012a, b). Figure 1 illustrates some of the concepts used in these two case studies using Monod rate functions (maintaining high DO, residual ammonia and intermittent aeration). The main objective of the control strategies was to maximize the rate differential between AOB and NOB growth to facilitate NOB out-selection by SRT control. The process was operated at high DO and ammonia residuals to maximize AOB activity over NOB activity. Another objective besides maximizing rate differential between AOB and NOB concerns substrate availability; during non-aerated phases more nitrite than ammonia is removed by anammox and denitrifying heterotrophs, thus limiting NOB growth when intermittent aeration is restarted.

MATERIALS AND METHODS

Long-term experimental pilot tests

Pilot #1: nitrite shunt – AVN controller

This pilot process was part of a larger configuration including a high rate activated sludge A-stage (Miller *et al.* 2012) for COD removal providing the influent for the AVN-controlled reactor (Regmi *et al.* 2014), which was followed by a post-anoxic anammox moving bed bioreactor allowing for a final polishing of residual nitrogen compounds (see Appendix A for configuration, available online at http://www.iwaponline.com/wst/071/022.pdf). To impose conditions favorable for NOB out-selection and to provide an effluent suitable for anaerobic ammonia oxidation polishing, an aeration controller was developed which uses online *in situ* DO, NH_4^+-N, NOx($NO_2^- + NO_3^-$) sensors. The AVN controlled the aerobic duration with the goal of maintaining equal effluent NH_4^+-N and NOx-N in the AVN reactor at all times and it maintained the DO at a desired set-point of 1.6 mg/L during the aerated period. The strategy was implemented in the model, and performance data were used to verify model parameter values.

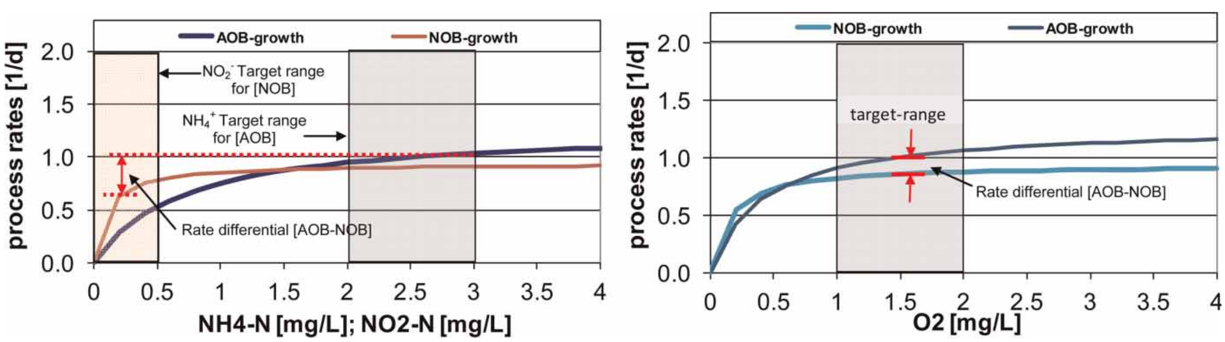

Figure 1 | Monod functions describing rate and substrate affinities and competition under pilot target operational conditions for NH_4^+-N, NO_2^--N and DO. Target ranges for both case studies are those where AOB growth rates are higher than NOB rates. To limit the growth rate of NOBs, target NO_2^- into aerobic phases of the intermittent aeration must be low (left chart).

Pilot #2: mainstream deammonification – ammonia-based control

The pilot consisted of a 200 L rectangular tank divided into 10 sequential aerobic and anoxic zones (D1–D10) with DO and ammonia-based controls (see Appendix A for pilot configuration). Oxygen level was maintained at 1.5 mg/L in the aerated cells where oxygen was measured using LDO sensors (HACH, Düsseldorf, Germany). NH_4^+-N was measured using a NH4D sc ammonium sensor (HACH, Düsseldorf, Germany). NH_4^+-N concentration in the last cell (D10) was maintained above 2 mg/L. The aerobic SRT was modified by adjusting wasting rates as needed to maintain target NH_4^+-N concentration in cell D10. Anammox seed was added to the reactor on a daily basis using sludge from a full-scale sidestream DEMON reactor, and AOB seed was added from a bench-scale sidestream reactor. Anammox was selectively retained in the system using sieves with mesh size No. 70 and No. 120 (or 212 and 125 μm, respectively). The performance data and profiles were used to verify model values.

Modeling approach

The model used for the simulations was a general model that included a two-step nitrogen model (including AOB, NOB and anammox) which was proposed by Jones *et al.* (2007) (Table 1). The simulator used was BioWin v3.1 (Envirosim, ON, Canada). The oxygen half saturation concentrations for AOB, NOB and anammox were modified using the previously calibrated values reported by Al-Omari *et al.* (2012a, b). It was observed that ammonia removals in the model were lower than measured when using the default total inorganic carbon half saturation concentration (K_{CO2} of 0.1 mmol/L). To match the measured removal rates, K_{CO2} of 1.5 mmol/L was calibrated using ammonia removal profiles in the DC Water deammonification pilot reactor. Supporting data were found in the literature where the use of 4 mmol/L for AOB was recommended by Wett (2005) in sidestream processes, and Guisasola *et al.* (2007) suggested that AOB were limited by inorganic carbon availability at concentrations as low as 3 mmol/L while the NOB were not limited even at concentrations below 0.1 mmol/L. Based on this observation, Pilot #2 operation was modified to increase the alkalinity in the feed to achieve effluent concentration above 4 mmol/L. To model the impact of inorganic carbon on AOB, separate half saturation values for inorganic carbon limited growth were specified (Table 1). The model was used to compare features of process control strategy used for NOB out-selection by simulating two controllers (i.e. AVN vs. ammonia) side by side. While the control strategy and parameters are selected

Table 1 | Heterotrophic biomass (BioWin v3.1) and autotrophic biomass model parameters (default parameters – Jones *et al*. 2007)

Parameter	AOB	NOB	Anammox	OHO
Maximum spec. growth rate (1/d)	(0.9)	(0.7)	(0.1)	(3.2)[a]
Arrhenius on maximum spec. growth rate	(1.072)	(1.06)	(1.1)	(1.029)
Substrate (NH_4) half sat. (mgN/L)	(0.7)	–	(2)	–
Substrate (NO_2) half sat. (mgN/L)	–	(0.05)	(1)	(0.01)
Aerobic decay rate (1/d)	(0.17)	(0.17)	(0.019)	(0.30)
Anoxic/anaerobic decay rate (1/d)	(0.08)	(0.08)	(0.0095)	(0.30)
Nitrous acid inhibition constant (mmol/L)	(0.005)	(0.075)	–	–
NO_2^--N inhibition constant (mgN/L)	–	–	(1000)	–
NO_2^--N toxicity constant (L/(d mgN))	–	–	(0.016)	–
DO half sat. (mgO_2/L)	**0.4** (0.25)	**0.14** (0.5)	**0.05** (0.01)	**0.45** (0.05)
Total inorganic carbon half sat. (mmol/L)	**1.5** (0.1)	(0.1)	(0.1)	–
Yield (mgCOD/mgN) – autotrophs	(0.15)	(0.09)	(0.114)	–
Yield (mgCOD/mgN) – OHO	–	–	–	–
Aerobic	–	–	–	(0.67)
Anoxic	–	–	–	(0.54)

Values in brackets are default values. Values in bold are modified values. DO half saturation values for AOB, NOB and anammox were previously calibrated. *Source:* Al-Omari *et al*. (2012a, b).
[a]This is under aerobic conditions. Under anoxic conditions the growth rate is reduced by 50%.

based on the goal of the treatment required, the objective here was to demonstrate some of the features that the AVN controller had over the ammonia-based controller by simulating Pilot #1 using both control strategies side by side. The model was also used to evaluate the impact of seeding AOB (AOB bioaugmentation) from the sidestream process on NOB out-selection. In addition, the model was used to anticipate potential improvement in pilot performance when artifacts associated with pilot reactors such as reactor depth and retention efficiency of NOB in the physical selector were addressed.

RESULTS AND DISCUSSION

AVN vs. ammonia-based control – modeling

A simulation of the AVN reactor operation using average loading conditions to reach steady state was used as the starting point for dynamic simulations. The model was able to predict average NH_4^+-N, NO_3^--N and NO_2-N after increasing the heterotrophs oxygen inhibition half saturation coefficient for denitrification (K_{io_2}) to 0.45 mg/L. The same value was used previously in the Blue Plains Advanced Wastewater Treatment Plant whole plant calibrated process model to match nitrogen removal in the secondary carbon removal system that was bioaugmented with nitrifying sludge. It was not feasible to calibrate the model using dynamic input for Pilot #1 due to the lack of a proper AVN controller in the model. Instead, the model was calibrated using Pilot #2 profile data (Figure 4) and verified using average performance data from Pilot #1 as mentioned earlier. To evaluate the AVN controller, the simulation of Pilot #1 was operated using both AVN and ammonia-based controls. To mimic the AVN control strategy for dynamic input, the reactor influent flow rate was varied to reflect a step change in influent mass loading (kg/d) by +25% of the average loading rate for 12 h and −25% of the mass loading rate for the following 12 h (Figure 2).

Comparing the two simulation outputs revealed that nitrogen removal efficiency was increased by approximately 7.3% under the AVN control. Also, the stable alkalinity level in the reactor for the AVN simulation compared to that for the ammonia-based control was noteworthy. It was important to realize that the controller under the AVN strategy controls the NH_4^+-N removal rate based on denitrification capacity, i.e. the aeration period was adjusted so that NH_4^+-N was nitrified only if the same amount of nitrogen can be removed via denitrification. This balancing action allows for more efficient use of the biodegradable carbon for nitrogen removal, recovery of alkalinity and applying SRT pressure on NOB. In the ammonia-based control simulation, aeration is increased during high loading conditions to maintain nearly constant effluent NH_4^+-N level. By increasing aeration time, more COD is aerobically oxidized and more bicarbonate is stripped and consumed by nitrifiers. Consequently, NH_4^+-N oxidation rates slow down due to inorganic carbon limitation.

In return, the controller increases the aeration time even further, which again causes further COD oxidation and alkalinity suppression. This continues until the NH_4^+-N concentration cannot be reduced any further.

Simulation indicated marginal increase in NOB repression, manifested in an increase of 1.7% in AOB/NOB ratio. It should be noted that effluent alkalinity from the pilot was <1.8 mmol/L. The low alkalinity level limited the AOB growth rates and decreased the potential to enhance NOB out-selection. However, this improvement can be significant when combined with improvements due to other mechanisms such as AOB seed, which will be discussed in the following section.

Impact of AOB seeding and SRT

Seeding AOB from a sidestream process that utilizes a short-cut nitrogen removal process can be beneficial to enhance NOB repression in mainstream processes with the aim of achieving the NO_2^--N shunt. Figure 3(a) illustrates the concept of seeding a tank with AOB-rich waste from a sidestream process where the difference in critical SRT between AOB and NOB increases with the AOB seed mass (Mseed) introduced to the mainstream tank to contribute to the critical biomass (Mcritical). The critical biomass was defined as the minimum mass of organisms in the system that is required to meet a target substrate concentration. Hence, critical SRT was defined as the minimum SRT required to maintain critical active biomass in the process.

It is assumed that 20% of the influent nitrogen load is recycled back from solids handling processes and treated in the sidestream process. Simulations of the AVN pilot reactor with (1) 50% seeding activity (assuming that 50% of the seed activity is lost due to the difference in temperature between sidestream and mainstream processes (Wett *et al.* 2011)) and (2) 100% seeding activity (assuming no loss of activity) were examined. The system SRT was reduced to maintain the same NH_4^+-N removal rate in the system. Figure 3(b) shows the simulation output for AOB and NOB under both seeding conditions. The simulation

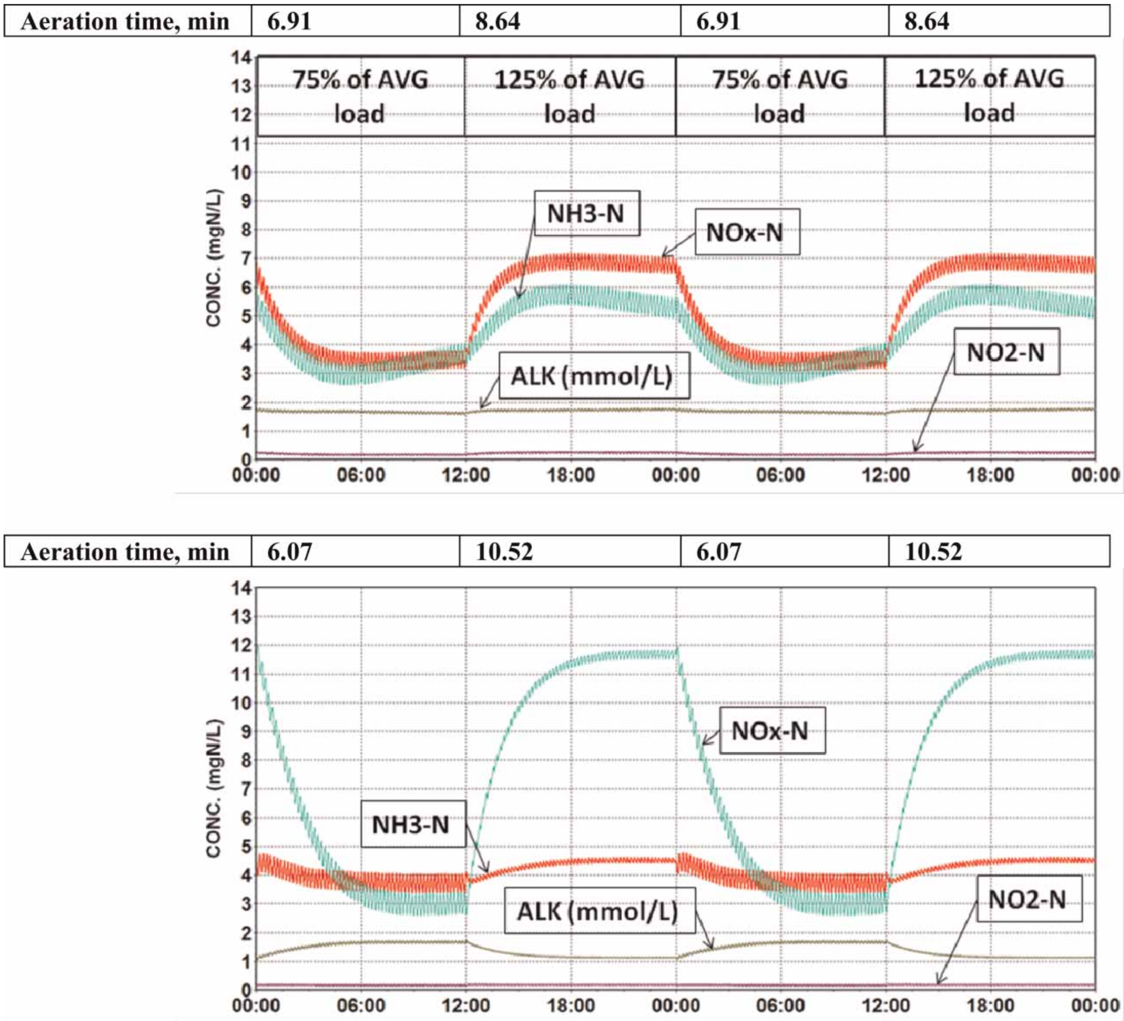

Figure 2 | Simulation output for AVN-based (top) and ammonia-based (bottom) controls for HRSD pilot reactor with 12 min cycle.

showed that the gap between the mass of AOB and NOB widened with increased AOB seeding rate, as evidenced by the AOB/NOB ratios. Supplementing the system with AOB from the sidestream process allows the system to operate at lower SRT with the same ammonia removal performance, but with lower NOB fraction.

Impact of retention efficiency and shallow reactors on NOB out-selection

Simulations of Pilot #2 reactor are compared to the actual measurement in Figure 4. The overall profiles of NH_4^+-N, NO_3^--N, NO_3^--N were closely predicted by the model. The model utilized activity measurement of retained sludge (mgN/gVSS·d) from the sieve apparatus to assess AOB, NOB and anammox retention efficiency. The model estimated an AOB/NOB ratio of 1.7 compared to 1.6 (for fully nitrifying systems) with effluent alkalinity of 2.9 mmol/L. However, when effluent alkalinity increased to 4.5 mmol/L, the model estimated an AOB/NOB ratio of 2.5 and effluent nitrite concentration of 3 mgN/L, which closely matched the measured levels.

To address the potential for NOB out-selection at full scale with regard to the impact of the inorganic carbon limitation on AOB growth and retention efficiency of NOB by the sieve (in the case of the DC Water pilot) where NOB may have attached onto the anammox granules, a simulation exercise was conducted. In this exercise, the retention of the various organisms was modified in the model to reflect an ideal separation of granular anammox bacteria and AOB and NOB and the depth of the reactors in the model was adjusted to mimic that of full-scale tank depth. The shallow pilot reactors suffer from high gas mass transfer and CO_2 stripping is significant. The increased

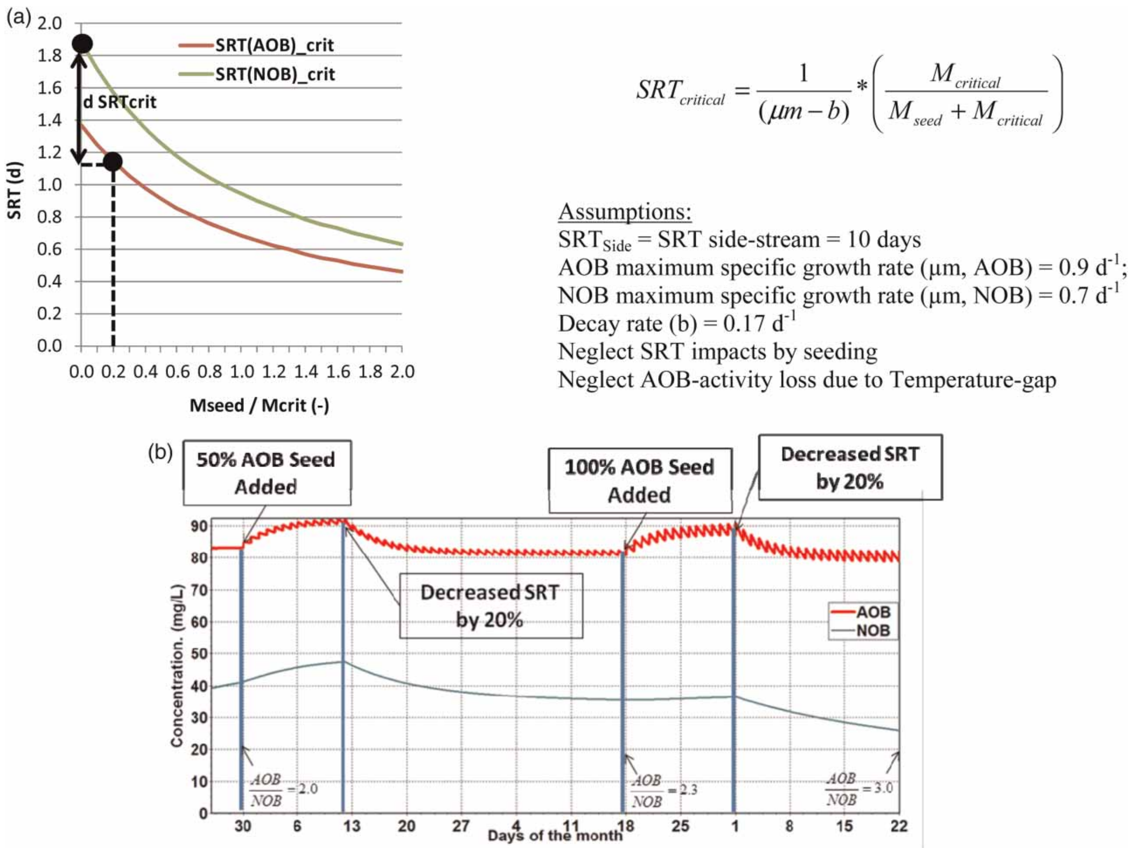

Figure 3 | (a) Bioaugmentation vs. SRT conceptual model: bioaugmenting AOB only from sidestream process with successful NOB out-selection. The two curves are associated with AOB and NOB where the SRTs required to establish the critical masses of AOB and NOB without bioaugmentation are 1.4d and 1.9d, respectively. By increasing the mass of AOB augmented from sidestream, the required SRT to establish the same critical mass in mainstream is reduced. This widens the gap between AOB and NOB SRT requirement, and thus allows for better control on NOB washout. (b) Simulation of Pilot #1 reactor with AVN control showing 100 and 50% seed mass rates and SRT variation.

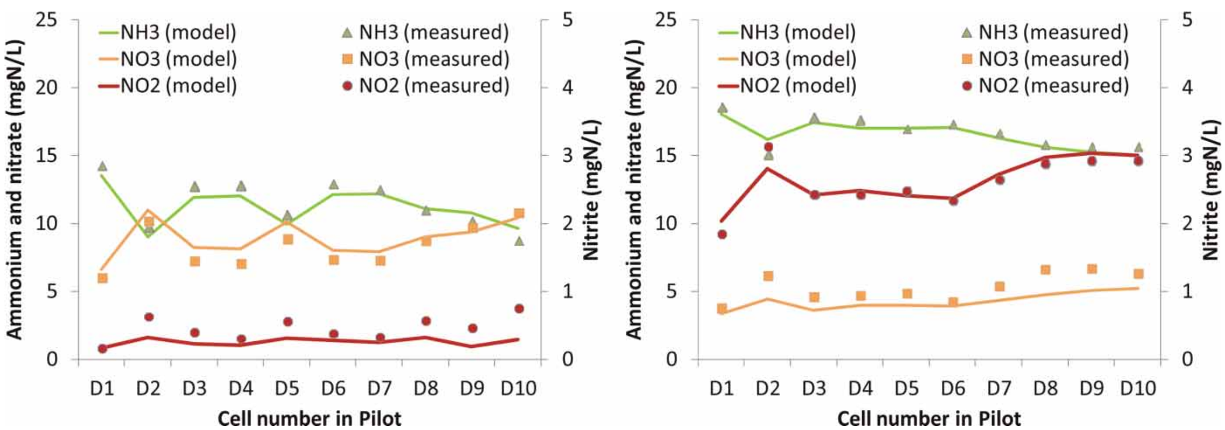

Figure 4 | Simulation and measured profiles of Pilot #1 ammonia-based control; (left chart) with effluent alkalinity concentration of 2.9 mmol/L; (right chart) with effluent alkalinity concentration of 4.5 mmol/L. K_{CO2} for AOB is 1.5 mmol/L in both cases.

depth could therefore counteract this artifact of shallow reactors. Table 2 presents a comparison between the pilot reactor performance with and without these hypothetical improvements (i.e. better separation of anammox and AOB and NOB in the sieve, and lower CO_2 stripping in deep tanks). The model predicted an AOB/NOB ratio of

Table 2 | Impact of selective retention and tank depth on NOB out-selection

Parameter	Pilot	Improved selective retention	Improved selective retention + deep tankage
Anammox retention efficiency, %	73	90	90
AOB retention efficiency, %	35	20	20
NOB retention efficiency, %	52	20	20
Tank depth, m	0.3	0.3	9.0
AOB/NOB ratio	1.8	2.9	7.1

7.1 when both retention and tank depth are optimized. The optimized model was then used to determine the potential savings in carbon addition in the form of acetate between a conventional nitrification-denitrification system and a system with nitrogen shortcut (i.e. repressed NOB).

The model showed that for nitrogen removal efficiency of approximately 90% and effective (i.e. 70%) NOB out-selection, the acetate saving due to nitrogen shortcut was 60% compared to conventional nitrification-denitrification. However, a validation of the model will be required either with full scale or with a modified pilot reactor to confirm the hypotheses introduced.

CONCLUSIONS

In this paper, a model-based approach of the key mechanisms for shortcut nitrogen removal to facilitate mainstream deammonification was presented. The model served as a useful tool to separate the impact of individual mechanisms for NOB out-selection and to identify artifacts associated with bench-scale reactors. The model's predictive power allowed for anticipating the need for alkalinity addition to the pilot reactors to improve NOB out-selection, which was confirmed by measured nitrite accumulation. It also illustrated the benefit of using the novel AVN controller over the ammonia-based control by managing carbon removal and recovering alkalinity, demonstrated the impact of AOB seeding and SRT on NOB out-selection, and showed the importance of applying aggressive SRT for effective NOB out-selection. The model was used in a hypothetical scenario demonstrating potential external carbon savings of 60% that would be realized by converting a conventional nitrification–denitrification system to mainstream deammonification exemplified by the Blue Plains WWTP case study.

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