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Modelling the effect of salt from road runoff on nitrification of a wastewater treatment plant

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ABSTRACT

Salt (NaCl) that is being dispersed on the roads to prevent the formation of ice and snow can have positive and negative effects on nitrification rates in wastewater treatment plants (WWTPs). Based on experimental data, a numerical model has been derived to describe these effects. The numerical model has been successfully implemented in the SIMBA# simulation software and tested on a real case study, the Freistadt WWTP, located in Upper Austria. A number of parameters impacting nitrification have been investigated: inflow salt concentration, duration of the salt loading, temperature during salt loading, and increasing volumetric inflow to the WWTP during salt loading events. Simulation results revealed that salt concentration lower than 1 g NaCl/l brought improvement in nitrification rates. However, when this threshold was exceeded, inhibition of nitrification occurred. Furthermore, prolonged salt dosing exposure times brought amplification of both positive and negative effects on removal rates. Results show that salt concentration and salt load have the biggest impacts on nitrification.

Key words: dynamic simulation, nitrification, salt, SIMBA#, wastewater treatment

HIGHLIGHTS

- A numerical model for describing the effect on salt on the maximum rate of nitrification in activated sludge plants was developed.
- The numerical model was implemented in the SIMBA# simulation software.
- The model was successfully tested for various scenarios developed for a real wastewater treatment plant.

INTRODUCTION

In many temperate climates, salt (NaCl) is dispersed on the roads and pavements to prevent the formation of ice and snow. Salt runoff flows into the sewer system during snow-melting or rain events in combined sewers and is thus transported to wastewater treatment plants (WWTPs). The increased salt in the runoff increases the chloride concentrations in the influent of WWTPs. Flesch (2020) reported that WWTP operators recorded operational impairments with higher chloride concentrations. These impairments included elevated effluent nitrogen and phosphorus concentrations, the break-up of sludge flocs, sludge settling problems, floating sludge on top of the secondary clarifier, etc.

Pernetti & Palma (2005) examined the impact of continuous and shock salt loadings. It was noted that autotrophic and heterotrophic bacteria respond differently to the type of salt loadings and salt concentrations. Shock salt loading caused respiration inhibition of 4–84%; however, the bacteria adapted quickly to continuous loadings. The biggest impactor on autotrophic and heterotrophic bacteria's oxygen uptake rates are salt concentration and time of exposure of bacteria to salt (Flesch 2020; Tauber *et al.* 2021). Laboratory-scale experiments showed that there were no negative effects on autotrophic and heterotrophic bacteria when the salt concentration was below 1 g NaCl/l whereby for 75% of these tests a positive increase in both autotrophic and heterotrophic oxygen uptake rates was measured (Flesch 2020). Conversely, when the salt concentration was higher than 1 g NaCl/l, the oxygen uptake rate decreased significantly. The hindering salt impacts influenced the WWTP only in the short to medium term. Microorganisms could adjust quickly to the inhibiting and newly created conditions. After the end of the salt event, the activity of the microorganisms normalized after about 4–5 days. Microorganisms showed similar behaviour also in submerged biofilters (Flesch 2020).

Aslan & Simsek (2012) performed tests with submerged biofilters adding various salt loadings (0–40 g NaCl/l). They observed an increase in the activity of autotrophic and heterotrophic bacteria at a concentration of 1 g NaCl/l. Likewise, there was a decrease in activity at higher concentrations. At a salt concentration of 40 g NaCl/l, there was a 60% diminishment in ammonium oxidizing rate and nitrite production rate. Wang *et al.* (2005) examined the impact of different salt concentrations on oxygen uptake rates and removal rates of total organic carbon in activated sludge systems. Both parameters exhibited an increase in performance for the salt concentration of less than 1 g NaCl/l and a decrease in performance when the chloride concentration exceeded the threshold of 1 g NaCl/l. Tauber *et al.* (2021) and Flesch (2020) reported that concentrations of salt higher than 1 g NaCl/l influenced the structure of the sludge floc particles. Higher concentrations led to the break-up of sludge particles and to an increase in the sludge volume index. Furthermore, the settling characteristics of the secondary clarifier were impaired and a floating sludge layer formed on the water surface of the secondary clarifier.

Chloride concentrations from road salt runoff in the inflow of WWTPs are reported in the range of a maximum 2–3 g NaCl/l (Flesch 2020). In wastewater treatment, these concentrations are generally considered as moderate concentrations. Higher concentrations (>10 g NaCl/l) only occur in coastal areas or from specific industrial discharges. The available literature on these lower salt concentrations is very scarce; thus, the exact effects of salt loading on WWTPs are still being researched.

The main objectives of this study were to develop a numerical model for salt impact on nitrification and to test the numerical model on a case study (Freistadt WWTP) to show the effects of increased salt concentrations on treatment performance.

MATERIALS AND METHODS

Development of a numerical model for salt impacts on nitrification

Oxygen uptake rates measured by Tauber *et al.* (2021) and Flesch (2020) were used as a measure of the activity of nitrifying bacteria and thus to develop a numerical model for the salt impacts on nitrification. Empirical functions relating to the maximum rate of nitrification and the salt concentrations were approximated using MSExcel®. The maximum nitrification rate was defined as a function of salt concentration. The SIMBA# modelling software does not provide a direct mechanism for modelling the impact of inhibitory chloride concentrations on WWTPs. Thus, the developed numerical model for salt impacts had to be implemented in the SIMBA# software, i.e. more specifically in the Activated Sludge Model 3 (ASM3; Henze *et al.* 2000) which is the biokinetic model used in this study. In ASM3, the calculation of the maximum rate of nitrification μ_{AUT} was altered by replacing the original maximum rate of nitrification at 20 °C μ_{AUT20} with a modified maximum rate of nitrification including the salt dependency μ_{salt}.

Model of the Freistadt WWTP

The developed numerical model describing the impact of salt on nitrification was tested on the Freistadt WWTP with a design capacity of 30,000 PE. Near the city of Freistadt, a new highway is planned to be built. In this location, runoff from the additional highway surfaces will be drained to the combined sewer system and will end up at the Freistadt WWTP. Since the loading on Freistadt WWTP is near the upper limit of its capacity (Matzinger 2017), there is a concern that additional salt loads would jeopardize WWTP operation, i.e. that the plant will not be able to meet the required effluent standards.

The plant model of the Freistadt WWTP developed by Matzinger (2017) in SIMBA# (ifak 2022) was used for the simulations. In the calibrated model, the following SIMBA# sub-models have been used: influent generator; primary clarification; activated sludge tanks; secondary clarification; control models (aeration, waste sludge, return sludge); and digestion (ifak 2022). In this study, we applied the GMP (good modelling practice) Unified Protocol (Rieger *et al.* 2013). As the model was already calibrated and validated by Matzinger (2017), the first steps of the GMP Unified Protocol could be skipped in this study.

Scenarios

Influent data for the base scenario were derived from the Freistadt WWTP operational data of the year 2020 (the parameters available in the operational data set are presented in the Supplementary Material). The median value of the dry weather inflow was 4,000 m^3/d corresponding to a hydraulic load of 26,600 PE_{150} (people equivalent calculated with 150 l per person and day). The median values of the influent concentrations for BOD_5, COD, total N, and NH_4-N have been 450, 670, 48, and 26 mg/l, respectively. The median value of the organic load for BOD_5 (Biochemical Oxygen Demand in 5 days) and COD (Chemical Oxygen Demand) was 33,000 PE_{60} and 25,200 PE_{120}, respectively.

No data on the salt inflow concentrations have been available from the Freistadt WWTP. Thus, the simulation of salt dosing has been based on the following reasoning: The minimum inflow water temperature at the Freistadt WWTP was 7.3 °C in February 2020. This day was also marked as rainwater day in the operational dataset, indicating that this might have been a day at which increased salt concentrations happened. We thus selected this day as the day on which the salt dosing was applied resulting in the default inflow temperature at the day of salt dosing of 7.3 °C.

The scenarios for salt dosing are based on the parameters that have been identified as possible impacts on nitrification in activated sludge plants due to nitrification, i.e. salt concentration, duration of salt dosing, inflow water temperature, and inflow quantity. All the scenarios investigate the impact of a shock load of salt on ammonium removal. The salt shock load was applied on day 10 and was kept constant during the salt load period.

Table 1 summarizes the scenarios applied to test the developed numerical model. Scenario 1 applies different salt concentrations for 24 h, whereas in scenario 2, the salt load is doubled by applying the same concentrations for 48 h to examine salt dosing duration impacts. The effect of lower inflow water temperatures was evaluated in scenario 3, whereas in scenario 4, higher inflow volumes modelling more heavy rainfall events or larger amounts of snow melted, respectively. In both scenarios, the salt inflow concentration was 2 g NaCl/l and the duration of salt dosing was 24 h. The higher flow rates for scenario 4 resulted in hydraulic loads of 33,300, 40,000, and 46,700 PE_{150}, respectively. To keep the pollution loads on these days constant, the influent concentrations were decreased accordingly.

Table 1 | Salt dosing scenarios applied to the Freistadt WWTP

Parameter (unit)	Scenario	1	2	3	4
Salt concentration	(g NaCl/l)	0.5 1 1.5 2	0.5 1 1.5 2	2	2
Duration of salt load	(h)	24	48	24	24
Inflow temperature	(°C)	7.3	7.3	7.3 6 5 4	7.3
Inflow volume	(m^3/d)	4,000	4,000	4,000	4,000 5,000 6,000 7,000

RESULTS AND DISCUSSION

Development of a numerical model for salt impacts on nitrification

As mentioned before, the amount of salt concentration influences the ammonium removal efficiencies. Literature showed that when the salt concentration was greater than 1 g NaCl/l, ammonium removal bacteria showed inhibitory behaviour and when the salt concentration was less than 1 g/l, there were positive effects on activated sludge processes (e.g. Wang *et al.* 2005; Aslan & Simsek (2012); Tauber *et al.* 2021).

Measured oxygen uptake rates from Tauber *et al.* (2021) and Flesch (2020) showed an increase in the activity of ammonium oxidizing bacteria of up to 200% when the salt concentration was less than 1 g NaCl/l. When this threshold was exceeded, the inhibition was up to 48%. To approximate the measured data, three empirical equations were required (Figure 1), based on regression function fitting using MSExcel®, namely:

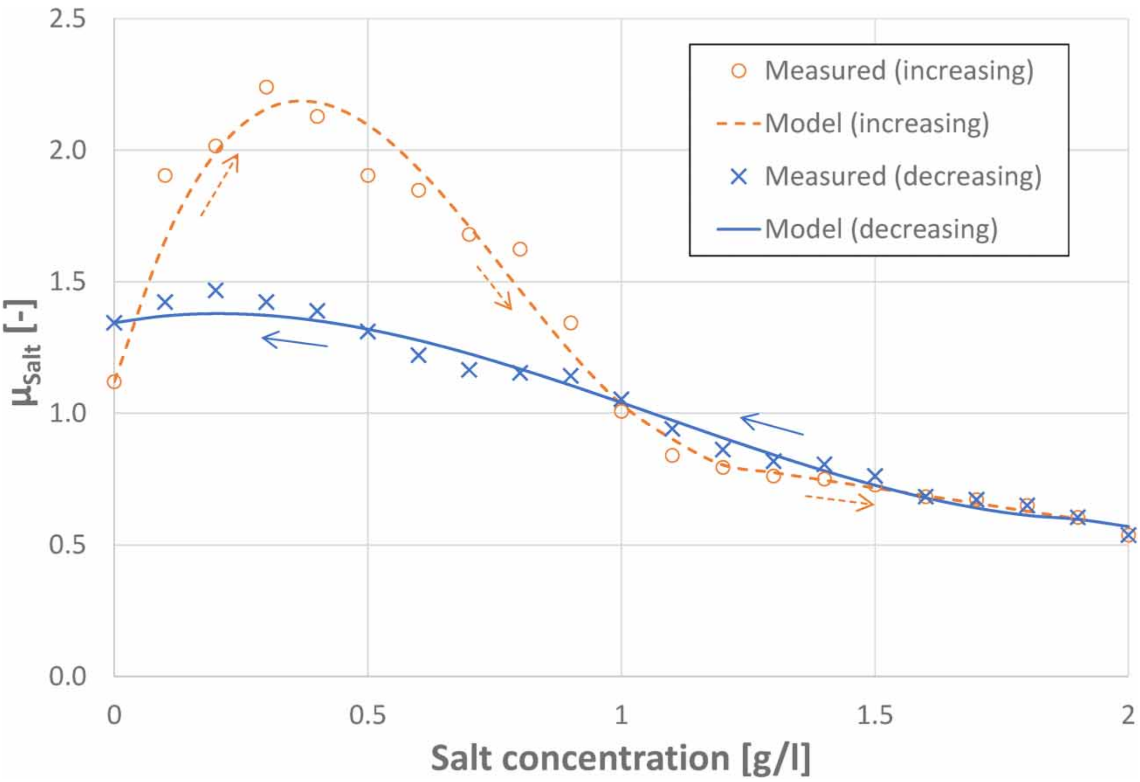

Figure 1 | Measured and modelled maximal rate of nitrification μ_{salt} with increasing (orange) and decreasing (blue) salt concentration. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wpt.2023.059.

1. Increasing concentration from 0 to 1.2 g NaCl/l:

$$\mu_{salt} = 4.9114C_{salt}^3 - 11.44C_{salt}^2 + 6.4432C_{salt} + 1.12 \quad (1)$$

2. Increasing concentration from 1.2 to 2 g NaCl/l:

$$\mu_{salt} = -0.2931C_{salt} + 1.1558 \quad (2)$$

3. Decreasing concentration from 2 to 0 g NaCl/l:

$$\mu_{salt} = 0.2919C_{salt}^3 - 0.9462C_{salt}^2 + 0.3508C_{salt} + 1.344 \quad (3)$$

where μ_{salt} is the factor modifying the maximum rate of nitrification depending on salt concentration (dimensionless); C_{salt} is the salt concentration (g/l).

The parameter μ_{salt} (m_{salt} in SIMBA#) and Equations (1)–(3) were implemented in the 'IEC Code' block of the SIMBA# software (ifak 2020). Details of the implementation in SIMBA# are described in Jovanović (2022).

The developed empirical model, i.e. μ_{salt} and Equations (1)–(3) for calculating μ_{salt}, can be used to modify the maximum nitrification rate in all ASM-type biokinetic models. The modified ASM-type biokinetic models can then be implemented in other available simulation software for activated sludge plants.

SIMULATION RESULTS

Scenario 1 – Varying salt concentrations

Figure 2 shows the simulation results of scenario 1 applying various salt inflow concentrations on simulation day 10 by comparing the predicted ammonium effluent concentration without the impact of salt and with increased salt concentrations, respectively. For a salt inflow concentration of 0.5 g NaCl/l (Figure 2(a)), the model predicted that ammonium removal was enhanced. The predicted ammonium effluent concentration dropped to a minimum of 2.5 mg NH_4^+/l on day 11 compared to 9 mg NH_4^+/l without the salt dosing. The model predicted no effects of salt dosing for a salt inflow concentration of 1 g NaCl/l (Figure 2(b)), showing that this concentration is a tipping point in the model between the positive effects of salt and inhibition. Increasing the salt concentration to 1.5 g NaCl/l (Figure 2(c)) and 2 g NaCl/l (Figure 2(d)) showed an increase in the predicted ammonium effluent concentration on day 11 by a margin of about 3–4.5 mg NH_4^+/l, respectively, compared to the scenario without salt dosing. Following the salt dosing event (24 h duration for this scenario), the model predicted the enhancing and inhibiting effects of salt on nitrification to last for a duration of a maximum of 4 days, which is in line with the results of Flesch (2020).

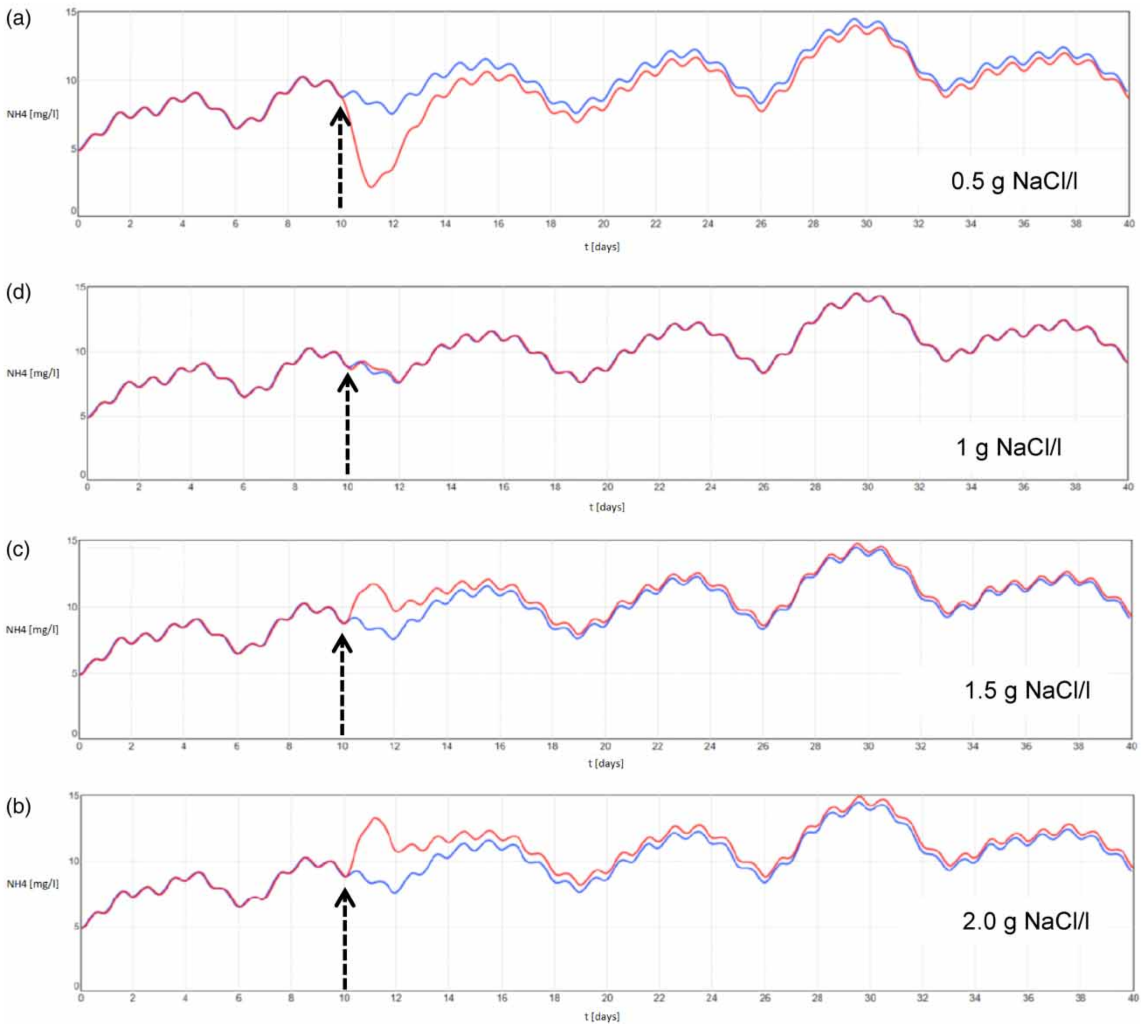

Figure 2 | Ammonium effluent concentrations with a dosing of various salt inflow concentrations for 24 h (blue: default, i.e. without salt dosing; red: with salt dosing). The arrow indicates the start of the added salt influent on simulation day 10. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wpt.2023.059.

Scenario 2 – Longer duration of salt dosing

Longer salt dosing times of 48 h duration brought amplification of both positive and negative effects. When the salt concentration was less than 1 g NaCl/l, the effluent quality significantly improved, as reflected by lower ammonium concentrations (Figure 3(a)). For higher inflow salt concentrations, significantly increased inhibition of nitrification occurred as compared with the case of 24-h salt dosing time (aligned with Figure 2). Figure 3(b) compares the results for 2 g NaCl/l. The maximum ammonium effluent concentration on day 11 increased to

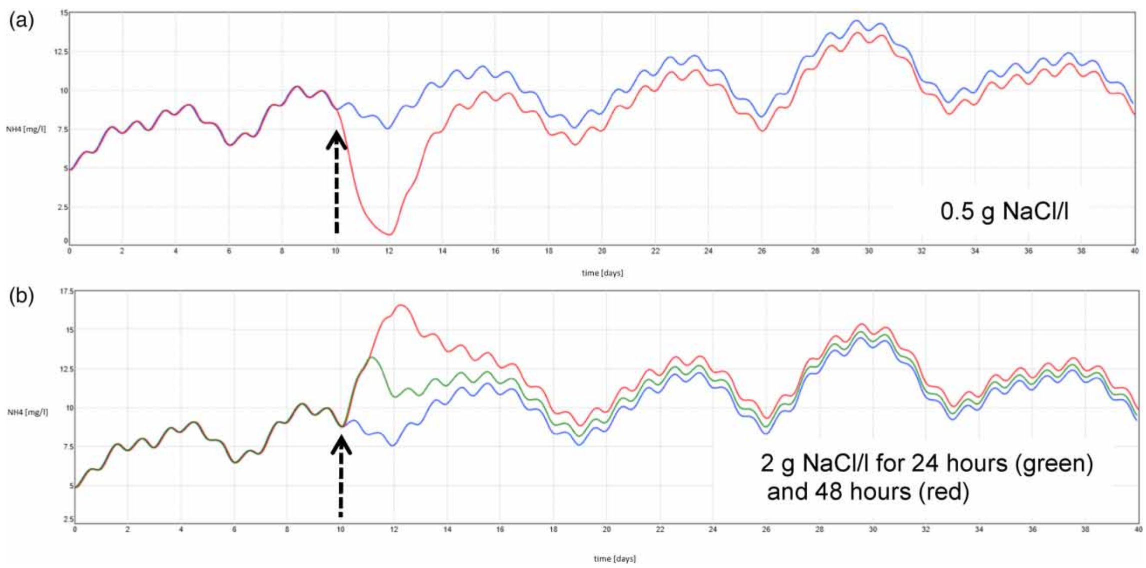

Figure 3 | Ammonium effluent concentrations with a longer dosing of salt in the inflow of the WWTP (blue: default, i.e. without salt dosing; other colours: with salt dosing). The arrow indicates the start of the added salt influent on simulation day 10. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wpt.2023.059.

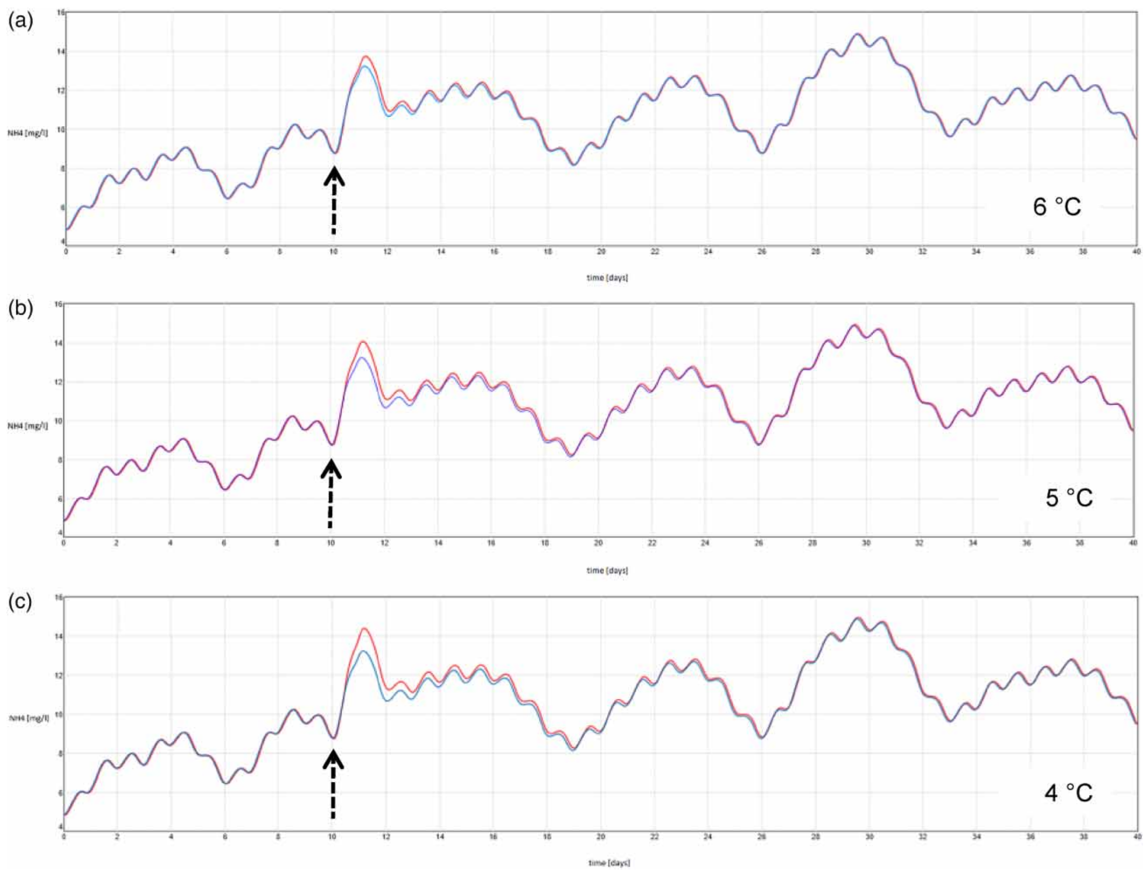

Figure 4 | Ammonium effluent concentration for different inflow water temperatures (blue: default, i.e. 7.3 °C; red: lower temperatures). The arrow indicates the start of the added salt influent on simulation day 10. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wpt.2023.059.

17 mg NH_4^+/l for the 48-h salt dosing compared with 12.7 mg NH_4^+/l for the 24-h salt dosing. Additionally, the plant took a longer time to recover from the salt impact.

Scenario 3 – Lower inflow temperatures

The effects of lower inflow water temperatures, with salt dosing of 2 g/l for 24 h (on day 10), are shown in Figure 4. Even if the inflow water temperatures dropped to 4 °C, there was only a 10% increase of the NH_4^+ effluent concentration, which was less than expected. However, it should be kept in mind that all ASMs are defined for the temperature range from 8 to 23 °C (Henze *et al.* 2000) and thus the prediction can be expected to be less accurate when applying the ASMs to lower wastewater temperatures.

Scenario 4 – Increased inflow of water quantities

The scenario 4 simulation results are shown in Figure 5. Based on the model predictions, with salt dosing at 2 g/l for 24 h on day 10, a temporary increase of inflow volume, due to a rain or snow-melting event, would not cause impairment in nitrification processes. At higher inflow rates, the model predicted that the lower pollutant influent concentrations had more effect on effluent concentrations than the increased salt load.

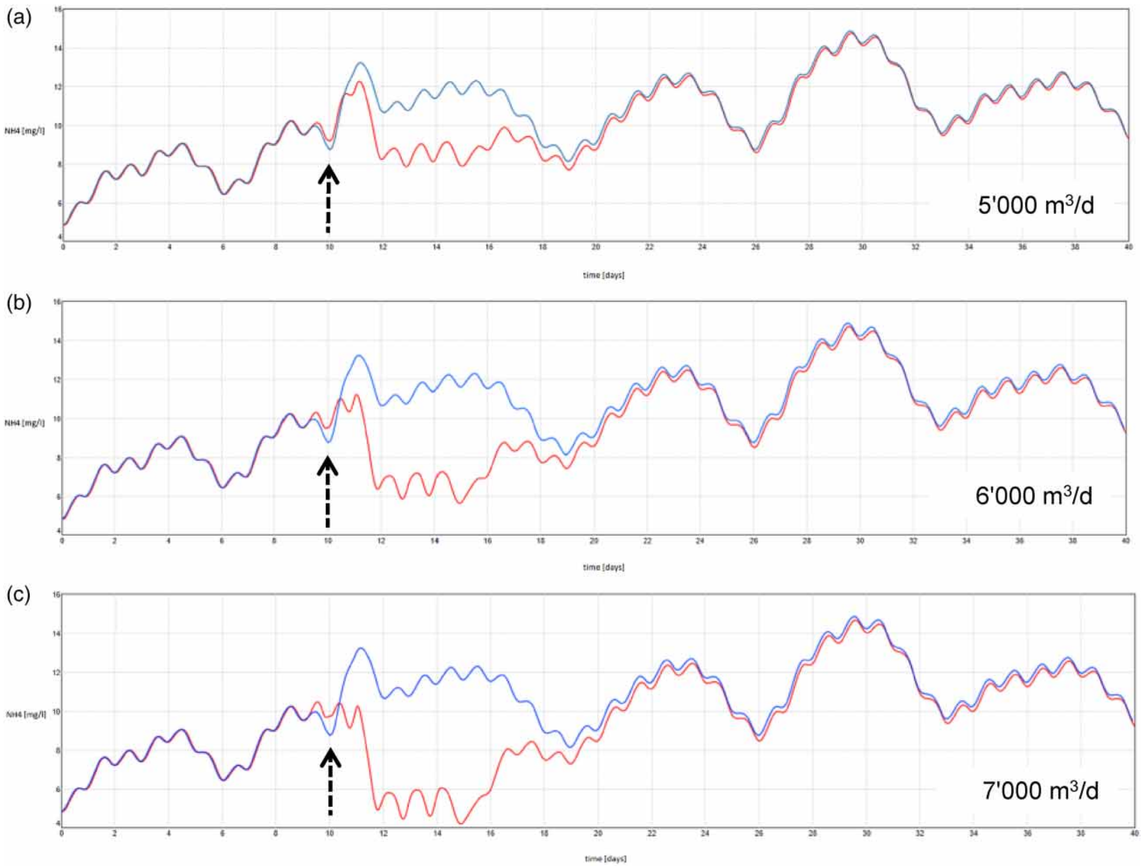

Figure 5 | Ammonium effluent concentration at increased inflow volumes (blue: default, i.e. 4,000 m³/day; red: increased inflow volumes). The arrow indicates the start of the added salt influent on simulation day 10. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wpt.2023.059.

CONCLUSIONS

From the results of this study, it can be concluded that:

- The numerical model developed for describing the effect of salt on the maximum rate of nitrification could match the experimentally determined oxygen uptake rates.
- The empirical model could be successfully implemented in the SIMBA# simulation software. The derived equations can be used to modify the maximum nitrification rate in any ASM-type biokinetic model in all commonly used simulators for activated sludge plants.

- When applying the implemented model to scenarios developed for a real WWTP, the effect of salt doses on the effluent ammonium concentrations could be shown. For an influent salt concentration of less than 1 g NaCl/l positive effects on nitrification can be expected, i.e. ammonium effluent concentrations decrease. For influent concentrations larger than 1 g NaCl/l inhibition of nitrification occurs, resulting in increased ammonium effluent concentrations.
- The results of the scenarios indicate that the effects of increasing salt concentrations and loads on nitrification are much greater than those due to decreased inflow water temperatures and increased inflow volume at the time of salt dosing.
- For a validation of the developed numerical model and its application, simulations with real data from a WWTP are still required.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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