

## Risk analysis of nitrification occurrence in pilot-scale chloraminated distribution systems

Jian Yang, Gregory W. Harrington, Daniel R. Noguera and Kala K. Fleming

### ABSTRACT

The implementation of chloramine disinfection introduces free ammonia into drinking water distribution systems, and free ammonia serves as an energy source for ammonia oxidizing bacteria that cause nitrification. The occurrence of nitrification may be affected by many factors including temperature, pH, water age, chloramine residual, and chlorine-to-ammonia application ratio. No studies have been conducted to quantitatively evaluate the individual and total contributions of these factors to the risk of nitrification occurrence. This study evaluated the individual and total contributions of pH and other factors on nitrification occurrence using factorial-designed pilot-scale chloraminated distribution system experiments. The pilot-scale systems were operated at pH values of approximately 7.0, 8.0, and 9.0. Logistic models were developed to quantify the contribution of pH and other factors to the risk of nitrification occurrence in the pilot-scale systems. Results showed that pH, total chlorine residual, hydraulic detention time, and temperature were the significant factors that influenced the risk of nitrification occurrence. However, none of these factors appeared to be dominant in predicting the risk of nitrification occurrence under the studied conditions. A simplified model was able to predict the risk of nitrification occurrence in the pilot-scale systems based on a combination of pH, temperature, and total chlorine residual. The developed logistic models provide an easy-to-use tool for drinking water utilities to manage operation strategies to minimize the risk of nitrification occurrence based on ambient conditions (temperature and pH) and operating parameters (water age and chloramine residual).

**Key words** | logistic, model, nitrification, risk analysis

**Jian Yang** (corresponding author)  
Earth Tech Inc., 200 Indiana Ave.,  
Stevens Point WI 54481,  
USA  
Tel.: 715/342-3052;  
Fax: 715/341-7390.  
E-mail: [jian.yang@earthtech.com](mailto:jian.yang@earthtech.com)

**Gregory W. Harrington**  
**Daniel R. Noguera**  
Department of Civil and Environmental  
Engineering,  
University of Wisconsin-Madison,  
Madison WI 53706,  
USA

**Kala K. Fleming**  
American Water,  
1025 Laurel Oak Rd., Voorhees NJ 08043,  
USA

### INTRODUCTION

Chloramination has been used as a secondary disinfection strategy in drinking water utilities to reduce levels of by-products such as trihalomethanes and haloacetic acids (AWWA 2000). This practice introduces free ammonia into distribution systems and this free ammonia serves as an energy source for ammonia oxidizing bacteria (AOB) which cause nitrification. Nitrification can degrade water quality by increasing nitrite and nitrate concentrations, reducing chloramine residuals, and promoting heterotrophic growth, which may cause an exceedance of the nitrite maximum

contaminant level (MCL) or violation of disinfectant residual standards in the Surface Water Treatment Rule (USEPA 1989). Nitrification occurrence has been reported by almost two thirds of drinking water utilities that use chloramines (Odell *et al.* 1996). While a review of the Information Collection Rule (ICR) database showed that 33% of surface water utilities used chloramines in 1999, a regulatory impact analysis predicted that the use of chloramines could increase to about 65% of these water systems (AWWA & EES 2000).

doi: 10.2166/aqua.2007.007

The occurrence of nitrification results from a combination of processes within distribution systems: decay of chloramines, release of free ammonia, and growth and inactivation of nitrifying bacteria (Harrington *et al.* 2003). These processes may be influenced by a variety of environmental factors (e.g. temperature and pH) and operational parameters (e.g. water age, chloramine residual, and chlorine-to-ammonia application ratio). Warm temperatures from 20°C to 30°C are usually considered favorable for the growth of nitrifying bacteria (Bowie *et al.* 1985). A survey of seven water utilities showed that nitrification occurred at temperatures of 8–26°C, but more than 80% of these occurrences were at relatively warm temperatures of 15–26°C (Odell *et al.* 1996).

Nitrification potential may also be sensitive to pH and may not change monotonically with pH values, because growth rates of nitrifying bacteria are maximized from pH 7.2 to 8.5 (Grady & Lim 1980; Bowie *et al.* 1985; Odell *et al.* 1996; Holt *et al.* 2000). In addition, other factors which contribute to nitrification occurrence may interact with pH. For example, free ammonia in the NH<sub>3</sub> form is the true enzyme substrate for AOB growth (Rittmann & McCarty 2001). The fraction of free ammonia in the NH<sub>3</sub> form increases with increasing pH. Thus, higher pH suggests the potential for accelerating the growth of nitrifiers. Counter to this, the effectiveness of AOB inactivation decreases with increasing pH (Oldenburg *et al.* 2002), which suggests nitrification occurrence may be more likely at higher pH due to less effective inactivation. Finally, the rate of chloramine decay decreases with increasing pH (Valentine *et al.* 1998), which suggests nitrification occurrence may be less likely at higher pH due to higher chlorine residual and lower ammonia concentration. Therefore, the interaction of these variables with pH produces a dependence of nitrification on pH that is difficult to predict. Nitrification episodes have been observed over a wide pH range from 6.6 to 9.7 (Odell *et al.* 1996), but the optimal pH for nitrification occurrence was reported to be about 8.5 (Harrington *et al.* 2002) and water utilities have reported that increasing pH above 9 may reduce nitrification occurrence (Skadsen & Sanford 1996).

Lengthening water age was reported to increase the potential for nitrification occurrence (Cunliffe 1991) and most nitrification problems have occurred in large

reservoirs and dead-end water mains (AWWA & EES 2000). While maintenance of total chlorine residual above 2 mg Cl<sub>2</sub>/L in distribution systems was reported as enough to prevent nitrification, this practice was not effective once nitrification had begun (Wilczak *et al.* 1996). Breakpoint chlorination has been considered one of the most effective strategies to stop nitrification after it has begun (Kirmeyer *et al.* 1995; Odell *et al.* 1996; Wilczak *et al.* 1996).

Studies on the effect of chlorine-to-ammonia application ratio on nitrification have been inconclusive for several reasons (Lieu *et al.* 1993; Odell *et al.* 1996). First, although chlorine-to-ammonia ratios determine free ammonia concentrations at the entry point of distribution systems, free ammonia is also released from chloramine decay as water moves through water mains (Harrington *et al.* 2002). This might explain why nitrification has been reported in distribution systems with a chlorine-to-ammonia application ratio of 5:1 (Odell *et al.* 1996). In theory, less free ammonia will enter the distribution system at this 5:1 ratio than at the ratio of 3:1 or 4:1. However, a survey found that systems with lower total ammonia levels (<1 mg/L) in water leaving the plants had more nitrification than systems with higher ammonia levels (Odell *et al.* 1996). One possible explanation to this seemingly contradicting observation could be that a lower ammonia level does not necessarily lead to lower true enzyme substrate level for AOB growth, which is in the NH<sub>3</sub> form and pH dependent as discussed earlier. In addition, Regan *et al.* (2003) found that the dominant AOB species in chloraminated distribution systems was *Nitrosomonas oligotropha*, which were considered to have a high substrate affinity and a low specific growth rate (Yoshioka *et al.* 1982; Rittmann & McCarty 2001; Park & Noguera 2007). The dominance of *Nitrosomonas oligotropha* suggests their adaptation to low ammonia concentrations in chloraminated systems and, therefore, higher ammonia concentrations may not necessarily lead to a higher risk of nitrification occurrence.

Literature findings show a comprehensive and qualitative understanding of the effect of ambient conditions and operational parameters on nitrification occurrence. However, few studies have been conducted to quantify the contribution of these factors to nitrification occurrence in chloraminated systems. Liu *et al.* (2005) and Yang (2005) developed semi-mechanistic steady state and dynamic

nitrification models, respectively. These models included some factors, such as water age and chlorine residual, to simulate nitrification in pilot-scale chloraminated systems. Alternatively, nitrification occurrence can be modeled statistically with high or low probabilities under certain conditions, considering nitrification occurrence has been reported under a wide range of pH, temperature, and other conditions (Odell *et al.* 1996). Such models are simple in comparison to mechanistic models, and therefore, if accurate, they can be useful predictors of risk factors in drinking water distribution systems. For instance, Volk & Joret (1994) and Gale *et al.* (1997) developed statistical models for predicting the risk of coliform occurrence in drinking water using easily measurable water quality parameters such as temperature and free chlorine residual. No such models have been published for predicting nitrification occurrence in drinking water. Thus, the objective of this research was to quantify the contribution of pH and other factors to the risk of nitrification occurrence in pilot-scale chloraminated distribution systems using statistical models.

## MATERIAL AND METHODS

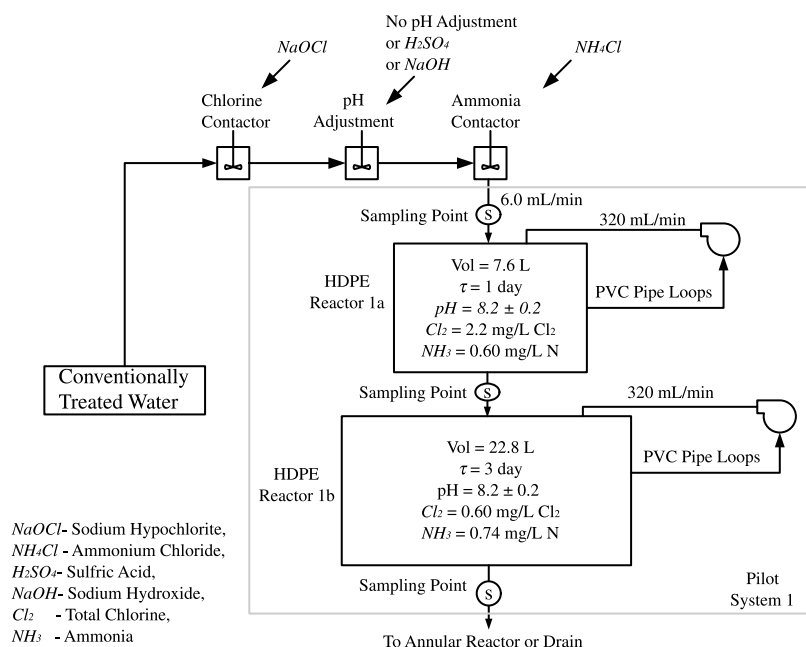
### Experimental design and setup

Pilot-scale distribution systems were set up at the Water Science and Engineering Laboratory on the campus of the University of Wisconsin-Madison. The pilot-scale distribution systems were fed continuously with conventionally treated water from Lake Mendota. The conventional treatment included alum coagulation, flocculation, sedimentation, and dual-media filtration processes. The treated Lake Mendota water was chloraminated with or without pH adjustment before entering the pilot-scale distribution systems. The operation of the pilot-scale systems began with two months of free chlorination at 60 mg Cl<sub>2</sub>/L to inactivate bacteria that might exist in the systems. Inactivation was verified with AOB counts, with heterotrophic plate counts (HPC), and with bacterial viability tests. After verifying the absence of AOB, HPC less than 100 cfu/ml, and live cell counts less than 100 cfu/ml, the systems were put on line and run for about 10 months. More details of the

conventional treatment processes and pilot-scale distribution system setup were addressed elsewhere (Harrington *et al.* 2002).

This study used factorial experiments with four factors: pH, total chlorine residual, chlorine-to-ammonia application ratio, and hydraulic detention time. Each factor was divided into two or three levels. Three experimental runs, Run 1, Run 2, and Run 3, were tested with three pH levels around 8.0, 7.0, and 9.0 in the pilot-scale systems, respectively. Chloramine residuals at the end of pilot-scale systems were controlled at 0.5 to 1.0 mg Cl<sub>2</sub>/L, 1.0 to 1.5 mg Cl<sub>2</sub>/L, or 2.0 to 2.5 mg Cl<sub>2</sub>/L, which covered the range of chloramine residuals used in practice. The free ammonia doses were also controlled at the entrance of the pilot-scale distribution systems with three chlorine-to-ammonia application ratios of 3:1, 4:1, or 5:1. Each pilot-scale system had two connected reactors with nominal detention times of 1 day and 3 days, respectively. The total nominal residence time was 4 days for each distribution system, which covered the range of typical water ages in full-scale distribution systems. The average distribution system retention time in a survey of more than 800 utilities was estimated to be 1.3 days (AWWA & AWWARF 1992). Furthermore, nitrification has been observed in distribution system networks and reservoirs with residence times from less than 1 day to more than 9 days (Kirmeyer *et al.* 1995; Odell *et al.* 1996; Lipponen *et al.* 2002).

Figure 1 shows the schematic of Distribution System 1 as an example pilot-scale system of Run 1. The system had two high-density polyethylene (HDPE) reactors connected in series with volumes of 2 gal (7.6 L) and 6 gal (22.8 L), respectively. The reactors were operated with a flow rate of approximately 6.0 ml/min, producing nominal detention times of 1 day and 3 days, respectively. Both reactors had a unique combination of controlled conditions including pH, chloramine residual, free ammonia concentration, and detention time, as shown in Figure 1. Each reactor was connected to a PVC pipe loop with 1.3 cm diameter and 7.6 m length. A recycle flow rate of approximately 320 ml/min in the pipe loop was maintained to make each reactor a completely mixed reactor and, at the same time, produce a water velocity of 4.2 cm/s to simulate typical low-flow conditions in real distribution systems. PVC and HDPE were used as the pilot-scale system materials to



**Figure 1** | Schematic of pilot-scale distribution system 1 during Run 1 from March 2002 to November 2002.

minimize reactions between chloramines and pipe/tank surfaces. As shown in Figure 1, samples were collected regularly at the influent of 1-day Reactor 1a, effluent of Reactor 1a (same as the influent of 3-day Reactor 1b), and effluent of 3-day Reactor 1b. Sampling data included concentrations of chloramines, free ammonia, dissolved oxygen, nitrite, nitrate, heterotrophic bacteria, and AOB in the bulk water. In addition, biofilm samples from the PVC pipe loops were collected during Run 1 but not used in this study. Those samples were used to study the microbial diversity of AOB in the pilot-scale systems, as reported elsewhere (Regan *et al.* 2002). Results from this sampling provided no conclusive evidence to suggest that growth was dominated by either biofilm growth or bulk water growth. For this paper, “free ammonia” is defined as the sum of  $NH_3$  and  $NH_4^+$  concentrations. Ambient temperature and pH were also monitored.

Table 1 summarizes the operating conditions of the pilot-scale distribution systems during three experimental runs. The six pilot-scale systems of Run 1 continued to run in parallel with a total nominal detention time of 4 days during Run 2 and Run 3. In addition, Pilot-scale Systems 5 and 6 in Run 2 were operated to duplicate two pilot-scale systems of Run 1. Pilot-scale Systems 5 and 6 in Run 3 were

operated to duplicate two pilot-scale systems of Run 2. As discussed earlier, the controlled operating conditions include pH, total chlorine residual, chlorine-to-ammonia application ratio, and hydraulic detention time. The average pH, total chlorine residual, and ammonia concentrations in the pilot-scale systems during the three experimental runs were 6.5 to 9.6, 0.16 to 3.9 mg- $Cl_2$ /L, and 0.26 to 1.5 mg  $NH_3$ -N/L, respectively, which covered the range of these operating conditions typically used in practice. Overall, 22 pilot-scale systems (44 reactors) were set up, including 4 duplicate systems (8 reactors) and 18 systems (36 reactors) with unique combinations of hydraulic and water quality conditions.

### Analytical methods

Total chlorine residuals were measured by using the DPD ferrous titrimetric method (Standard Methods 1998) and total ammonia concentrations were measured by a salicylate method (Method 10045, Hach Co., Loveland, CO). Nitrite and nitrate levels were determined by an ion chromatograph procedure (USEPA 1997). AOB were enumerated by using the most probable number (MPN) technique (Wolfe *et al.* 1990), HPC were measured by the

**Table 1** | Summary of operating conditions in pilot-scale distribution systems

Run	Pilot-scale system	Reactor	Nominal detention time (day)	Average pH	Average total chlorine (mg Cl <sub>2</sub> /L)	Average free ammonia (mg NH <sub>3</sub> -N/L)
Run 1 (2002)	1	1a	1	8.2	2.2	0.60
		1b*	3	8.2	0.60	0.74
	2	2a	1	8.2	2.8	0.57
		2b*	3	8.2	0.77	0.96
	3	3a	1	8.2	2.6	0.26
		3b*	3	8.2	0.47	0.53
	4	4a	1	8.1	3.9	1.0
		4b	3	8.3	1.8	1.5
	5	5a	1	8.1	3.4	0.82
		5b	3	8.3	1.6	1.0
	6	6a	1	8.2	3.4	0.33
		6b	3	8.3	2.0	0.56
Run 2 (2003)	1	1a	1	7.0	1.32	0.41
		1b*	3	7.7	0.16	0.66
	2	2a	1	6.9	1.6	0.61
		2b	3	7.4	0.48	0.69
	3	3a*	1	7.8	1.6	0.50
		3b*	3	8.2	0.98	0.51
	4	4a*	1	7.9	1.3	0.93
		4b*	3	8.2	1.2	0.94
	5	5a	1	8.2	1.7	0.55
		5b*	3	8.4	0.65	0.47
	6	6a	1	8.3	2.2	1.0
		6b*	3	8.4	0.80	1.1
	7	7a	1	7.4	2.6	0.69
		7b*	3	8.1	1.8	0.71
	8	8a	1	7.2	2.7	1.3
		8b	3	7.7	1.2	1.4

Table 1 | (continued)

Run	Pilot-scale system	Reactor	Nominal detention time (day)	Average pH	Average total chlorine (mg Cl <sub>2</sub> /L)	Average free ammonia (mg NH <sub>3</sub> -N/L)
Run 3 (2004)	1	1a	1	9.5	1.4	0.60
		1b	3	9.2	1.1	0.54
	2	2a	1	9.5	1.2	0.54
		2b	3	9.3	0.95	0.60
	3	3a	1	9.2	1.1	1.1
		3b	3	9.1	1.0	1.2
	4	4a	1	9.6	1.4	1.2
		4b	3	9.4	1.2	1.3
	5	5a	1	6.5	1.7	0.99
		5b	3	6.8	0.61	0.87
	6	6a	1	6.5	1.8	0.59
		6b	3	6.5	0.64	0.50
	7	7a	1	9.0	2.3	0.62
		7b	3	9.0	1.9	0.72
	8	8a	1	8.9	2.0	0.65
		8b	3	8.7	1.8	0.74

\*Average operating conditions prior to nitrification episode.

spread plate method with R2A agar (method 9215-C, *Standard Methods* 1998) and bacterial viability tests were conducted using the LIVE/DEAD BacLight™ bacterial viability kit (Molecular Probes Inc., Eugene, Ore). System pH and temperature were monitored with a pH meter and a digital thermometer, respectively.

### Logistic models

Logistic models were developed to evaluate the effect of pH and other factors on the risk of nitrification occurrence by analyzing experimental data from reactors that underwent nitrification and from reactors that did not undergo nitrification. These models are usually considered to be

more appropriate than general linear regression models when the response variable is categorical, e.g. either 0 or 1 (Hosmer & Lemeshow 2000). Regression analysis of these logistic models was conducted by using SAS 9.1 (SAS Institute Inc., Cary, NC). The response variable ( $Z$ ) was categorical (0, 1) representing the event of nitrification occurrence. A value of 1 was used to represent nitrification occurrence in a reactor, while a value of 0 was used to represent the absence of nitrification in a reactor. Contributing factors included pH, temperature, total chlorine residual, concentration of free ammonia, and nominal detention time. Three types of logistic models of nitrification occurrence were developed based on a single factor or multiple combinations of the contributing factors.

Concordant and Akaike Information Criterion (AIC) were used to evaluate the performance of each developed logistic model (Hosmer & Lemeshow 2000). Concordant is the percentage of correct predictions assuming that if the estimated  $p$  is greater than or equal to 0.5 then the event is expected to occur and not to occur otherwise. AIC was used to compare the developed models (the smaller the AIC, the better the model is). AIC increases as the model concordant decreases or the model complexity (e.g. number of parameters) increases.

Type I models were based on a single factor and can be expressed as below:

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 pH \quad (1a)$$

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1(pH - pH_{opt})^2 \quad (1b)$$

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 T \quad (1c)$$

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 C_d \quad (1d)$$

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 \tau \quad (1e)$$

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 C_s \quad (1f)$$

In Equations (1a) to (1f),  $p$  is the possibility that nitrification will not occur in a pilot-scale reactor (i.e.,  $p$  is the possibility that the response variable  $Z = 0$ ),  $1 - p$  is the possibility that nitrification will occur in a pilot-scale reactor (i.e., risk of nitrification occurrence),  $\beta_0$  is the intercept,  $\beta_1$  is the coefficient corresponding to each individual factor,  $pH$  is the pH condition in the system,  $T$  is the temperature ( $^{\circ}\text{C}$ ),  $C_d$  is the total chlorine residual (mg  $\text{Cl}_2/\text{L}$ ),  $\tau$  is the nominal detention time (day),  $C_s$  is the free ammonia concentration (mg  $\text{NH}_3\text{-N}/\text{L}$ ), and  $pH_{opt}$  is the optimum pH for nitrification occurrence.

The optimum pH for AOB growth is reported to be from pH 7.2 to 8.5 (Grady & Lim 1980; Bowie et al. 1985; Odell et al. 1996; Holt et al. 2000). However, no conclusive results about the optimum pH for nitrification occurrence in drinking water distribution systems have been reported in the literature. In this study, this value was estimated by the cross-validation method,

which finds the value of a parameter that gives the developed model the best prediction. In Equation (1b), the function form of pH was tested with “ $(pH - pH_{opt})^2$ ” and compared with the linear form “pH” as shown later in this paper. The linear form “pH” assumes nitrification risk increasing or decreasing monotonically with pH, while the polynomial form “ $(pH - pH_{opt})^2$ ” assumes that nitrification risk reaches the minimum or maximum at a certain pH value. In summary, six Type I models were developed to test each of the five contributing factors of the individual contribution and significance to nitrification occurrence in the absence of the other factors.

A Type II model was developed with a combination of the five contributing factors, with the assumption that these five factors were independent. The Type II model was expected to be more accurate than the Type I models because these five factors might contribute to nitrification occurrence simultaneously. The model is expressed as follows.

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1(pH - pH_{opt})^2 + \beta_2 T + \beta_3 C_d + \beta_4 \tau + \beta_5 C_s \quad (2)$$

In Equation (2),  $\beta_0$  is the intercept and  $\beta_1$  to  $\beta_5$  are the coefficients corresponding to each factor. The function form of pH was applied with “ $(pH - pH_{opt})^2$ ” because results from Model 1a and 1b showed that “ $(pH - pH_{opt})^2$ ” was statistically superior to “pH”.

A Type III model was developed with the addition of interactions among the contributing factors to the Type II model. The interactions were between total chlorine residual and factors including pH, temperature, and nominal detention time. The Type III model might be more accurate than the Type II model if the interactions among these factors also contribute to nitrification occurrence. The model is expressed as follows.

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1(pH - pH_{opt})^2 + \beta_2 T + \beta_3 C_d + \beta_4 \tau + \beta_5 C_s + \beta_{13} \cdot pH \cdot C_d + \beta_{23} \cdot T \cdot C_d + \beta_{34} \cdot C_d \cdot \tau \quad (3)$$

In Equation (3),  $\beta_{13}$  is coefficient of the interaction between pH and total chlorine residual,  $\beta_{23}$  is coefficient of

the interaction between temperature and total chlorine residual, and  $\beta_{34}$  is coefficient of the interaction between nominal detention time and total chlorine residual.

Temperature, pH, and nominal detention time were independent in this study. The first two conditions were environmental factors and the last condition was an operational parameter. These three factors might also interact with the concentration of free ammonia in terms of their contribution to nitrification occurrence. However, the contribution of free ammonia concentration to nitrification occurrence was estimated to be statistically insignificant, as discussed later in this paper. Therefore, the interactions between free ammonia concentration and other contributing factors were not included in the Type III model.

### Data extraction for logistic regression

Reactors that underwent nitrification provided conditions that led to nitrification for the logistic regression analysis. In this study, nitrification occurrence in a reactor was diagnosed when two continuous nitrite sample points and their 14-day average nitrite levels exceeded 0.1 mg  $\text{NO}_2^-$ -N/L. The period of 14-days was used to average nitrite levels because nitrite levels were sampled once or twice a week in this study. 14-day average nitrite levels averaged two to four observed nitrite levels to smooth out experimental noise and avoid false diagnoses of nitrification occurrence. The nominal detention time and the 14-day average conditions before nitrification including pH, total chlorine residual, free ammonia concentration, and temperature, were considered as the conditions that led to the nitrification occurrence. The condition-averaging period of 14-days was selected empirically to smooth out experimental noise and to be consistent with the averaging period used for nitrite levels. Figure 2 shows an example of these conditions prior to nitrification occurrence in Reactor 3b during Run 1. A nitrification episode occurred around 110 days as shown in Figure 2A. Figure 2B–E show that 14-day average conditions before the nitrification occurrence were 0.31 mg  $\text{Cl}_2$ /L, 1.1 mg  $\text{NH}_3$ -N/L, pH 8.2, and 30°C, respectively. Together with the nominal detention time of 4 days, these conditions were extracted as a group of conditions that led to nitrification for the logistic regression analysis.

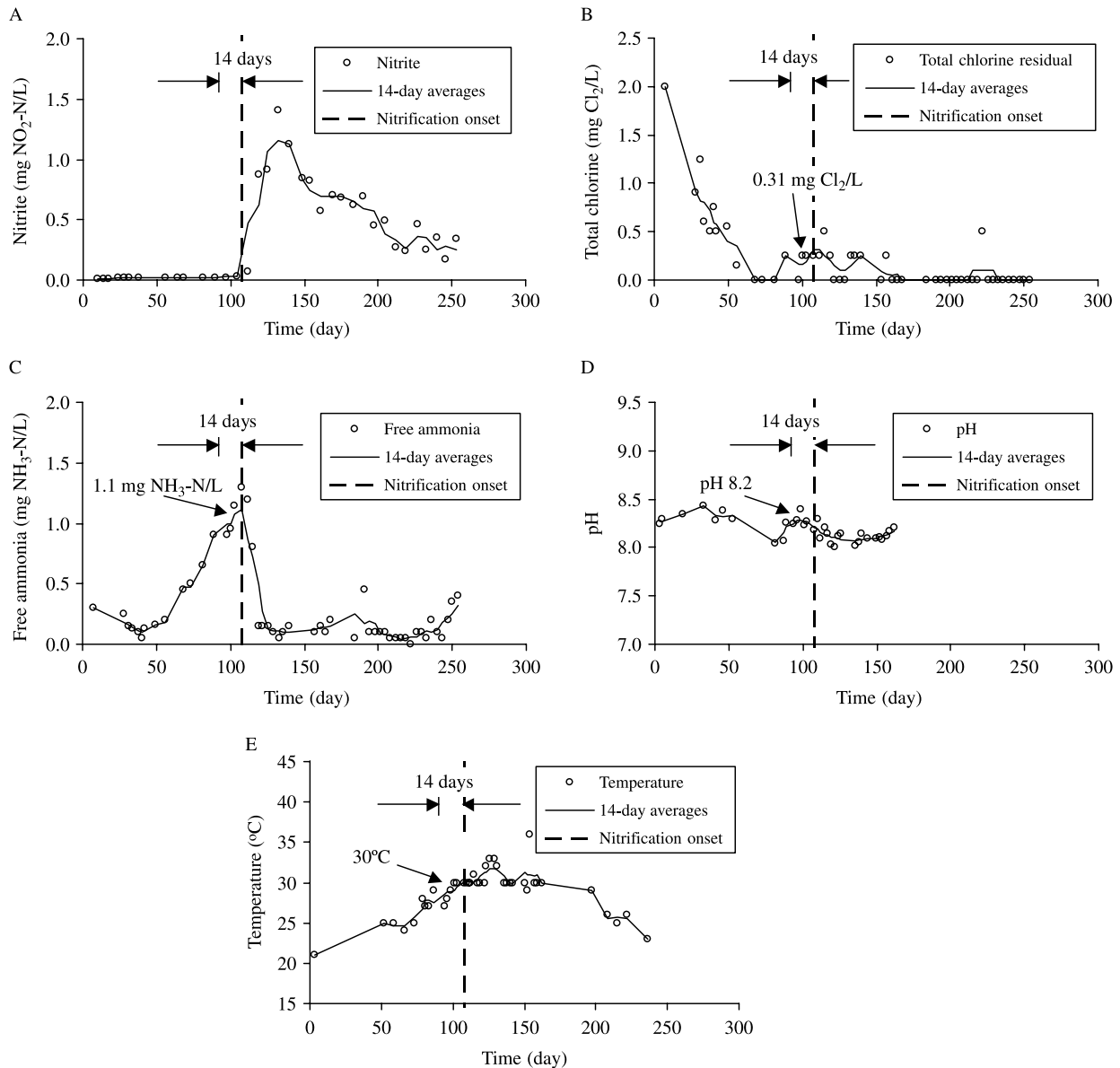
Each reactor that did not undergo nitrification provided groups of conditions that were considered not to lead to nitrification for the logistic regression analysis. These reactors were operated under ranges of contributing conditions including pH, total chlorine residual, free ammonia concentration, and temperature. Many possible choices of these contributing conditions could be extracted for the logistic regression analysis. Inclusion of every possible set of these conditions may introduce bias in the logistic regression analysis, as the number of conditions may significantly outnumber the previous number of conditions that led to nitrification. Therefore, only the minimum and the maximum of the four contributing conditions were extracted, which produced 8 ( $2 \times 4$ ) possible extreme conditions.

To illustrate how to extract the 8 extreme conditions, Figure 3 shows an example of the extreme condition at the minimum pH in Reactor 1a during Run 1. Reactor 1a was operated at pH 7.9 to 8.4, total chlorine residual from 1.0 to 5.2 mg  $\text{Cl}_2$ /L, free ammonia concentration from 0.31 to 1.4 mg  $\text{NH}_3$ -N/L, and temperature from 20 to 31°C. When the 14-day average pH reached the minimum pH of 7.9 as shown in Figure 3A, Figure 3B–D show a 14-day average total chlorine residual of 3.0 mg  $\text{Cl}_2$ /L, free ammonia concentration of 0.35 mg  $\text{NH}_3$ -N/L, and temperature of 27°C, respectively. These conditions together with the nominal detention time of 1 day were extracted as one group of conditions that did not lead to nitrification.

Table 2 shows the other 7 extreme conditions extracted from this reactor: the maximum pH condition, the minimum temperature condition, and so on. To verify if extracting extreme conditions introduced bias into the logistic regression analysis, 8 randomly selected groups of operating conditions were also extracted from the same reactor for the logistic regression model validation. Table 2 also shows an example of these eight randomly selected groups of conditions in Reactor 1a during Run 1. These randomly selected conditions were not used in the regression analysis but were used for model validation.

Overall, Table 3 summarizes the descriptive statistics of nitrification occurrence and the contributing conditions observed during the three pilot-scale runs. Table 4 summarizes 11 groups of conditions extracted from 11 reactors that underwent nitrification. As shown in Table 5, 33 reactors that did not undergo nitrification produced 264 ( $33 \times 8$ )





**Figure 2** | 14-Day average conditions prior to nitrification occurrence in reactor 3b during Run 1.

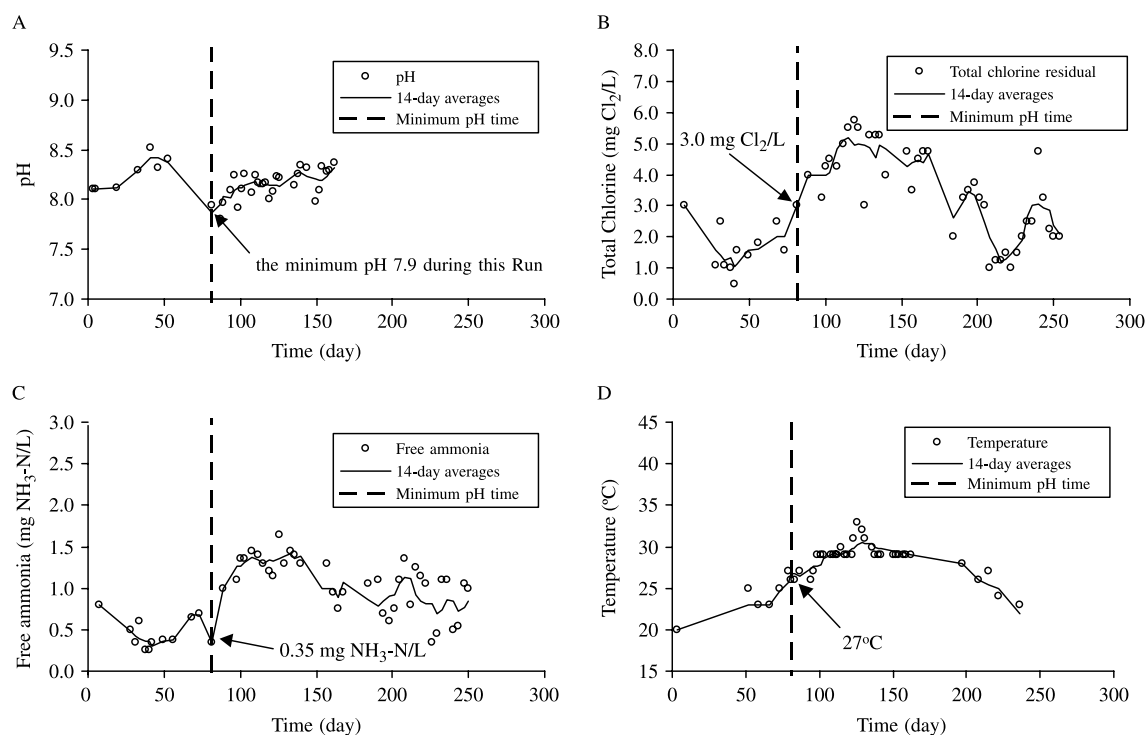
groups of conditions that did not lead to nitrification. In total, 275 groups of conditions in total were extracted to conduct the logistic regression analysis. The response variable was the event of nitrification occurrence. The contributing factors included pH, temperature, total chlorine residual, free ammonia concentration, and nominal detention time. Logistic models were developed by regression analysis within the ranges of these contributors. Model prediction of the risk of nitrification occurrence might not be accurate when the

developed models are applied to the system with conditions beyond these ranges.

## RESULTS AND DISCUSSION

### Experimental results

Table 4 summarizes the 14-day average conditions prior to nitrification occurrence in the 11 reactors that underwent



**Figure 3** | 14-Day average conditions in reactor 1a with no nitrification occurrence during Run 1.

nitrification. Nine out of these 11 reactors had a 4-day nominal detention time and 2 reactors had a 1-day nominal detention time, which indicates that longer water age may increase the risk of nitrification occurrence. As expected, longer water age may favor AOB growth, increase ammonia release, and increase difficulty to maintain sufficient chlorine residuals (Odell *et al.* 1996; Wilczak *et al.* 1996; Harrington *et al.* 2003).

The average pH over 14-days prior to nitrification occurrence was observed to range from 7.7 to 8.4. 14-day averages of total chlorine residual prior to nitrification occurrence were from 0.15 to 1.0 mg Cl<sub>2</sub>/L, which suggests that a total chlorine residual above 1.0 mg Cl<sub>2</sub>/L might be necessary to prevent nitrification in the pilot-scale systems. 14-day averages of temperature prior to nitrification occurrence ranged from 25 to 32°C compared with the overall observed range from 16 to 35°C, which suggests a warmer temperature preference for nitrification occurrence in the systems. 14-day averages of free ammonia concentration prior to nitrification occurrence ranged widely from 0.39 to 1.6 mg NH<sub>3</sub>-N/L, which is significantly higher than the AOB half saturation concentration of 0.02 to 0.1 mg NH<sub>3</sub>-N/L estimated from

semi-mechanistic modeling of these systems (Fleming *et al.* 2005; Yang 2005). Thus, free ammonia concentrations in the systems were not low enough to establish a limiting condition for nitrification occurrence.

Table 5 summarizes the 14-day average conditions in the 33 reactors that did not undergo nitrification, and provides the observed minimum and maximum 14-day averages of key variables over a 10-month experimental period. The average pH in these reactors ranged from  $6.5 \pm 0.5$  to  $9.4 \pm 0.2$ . Among these 33 reactors, 13 reactors had a 4-day nominal detention time and 20 reactors had a 1-day nominal detention time. Each reactor was operated under a set of controlled water quality variables including pH, total chlorine residual, free ammonia concentration, and temperature. For example, the 7<sup>th</sup> reactor in Table 5 was operated under a 1-day nominal detention time and an average pH of  $8.1 \pm 0.1$ . During the 10-month experiment, 14-day average values of pH, total chlorine residual, free ammonia concentration, and temperature in this reactor ranged from 7.9 to 8.4, 1.0 to 5.2 mg Cl<sub>2</sub>/L, 0.31 to 1.4 mg NH<sub>3</sub>-N/L, and 20 to 31°C, respectively. This 7<sup>th</sup> reactor did not undergo nitrification.

**Table 2** | Conditions that did not lead to nitrification in reactor 1a during Run 1

	$\tau$ (day)	pH	Total chlorine (mg Cl <sub>2</sub> /L)	Free ammonia (mg NH <sub>3</sub> -N/L)	Temperature (°C)
Extreme conditions selected for logistic regression analysis					
Minimum pH	1.0	7.9*	3.0	0.35	27
Maximum pH	1.0	8.4*	1.0	0.36	21
Minimum C <sub>d</sub>	1.0	8.4	1.0*	0.36	21
Maximum C <sub>d</sub>	1.0	8.1	5.2*	1.3	29
Minimum C <sub>s</sub>	1.0	8.4	1.1	0.31*	21
Maximum C <sub>s</sub>	1.0	8.2	4.6	1.4*	30
Minimum T	1.0	8.1	3.0	0.80	20*
Maximum T	1.0	8.2	4.9	1.4	31*
Randomly selected conditions for verification					
Random 1	1.0	8.1	5.0	1.3	29
Random 2	1.0	8.2	4.0	1.3	30
Random 3	1.0	8.3	2.4	0.78	22
Random 4	1.0	7.9	3.0	0.35	27
Random 5	1.0	8.3	2.5	0.92	26
Random 6	1.0	8.2	4.4	1.0	29
Random 7	1.0	8.3	1.2	1.1	25
Random 8	1.0	8.3	4.6	1.4	30

\*Extreme value of an extreme condition.

**Table 3** | Descriptive statistics of factors/variable for risk analysis of nitrification occurrence in the pilot-scale systems

Variable	Description	Count	Min	Max	Average	Std. deviation
Z*	Discrete (0 or 1)	275	0	1	0.040	0.20
pH	Continuous	275	4.1	10.5	8.3	1.0
T (°C)	Continuous	275	16	35	25	4
Total chlorine residual (mg Cl <sub>2</sub> /L)	Continuous	275	0.0	6.7	2.1	1.6
Free ammonia (mg NH <sub>3</sub> -N/L)	Continuous	275	0.030	2.7	0.85	0.56
Nominal detention time (day)	Discrete (1 or 4)	275	1.0	4.0	2.2	1.5

\*"1" indicates nitrification occurrence and "0" indicates no nitrification.

**Table 4** | Summary of 14-day average conditions prior to nitrification

ID	$\tau$ (day)	pH*	Total chlorine* (mg Cl <sub>2</sub> /L)	Free ammonia* (mg NH <sub>3</sub> -N/L)	Temperature* (°C)
1	1.0	7.7	0.72	1.3	30
2	1.0	8.0	1.0	0.57	32
3	4.0	7.8	0.15	0.59	29
4	4.0	8.1	0.60	0.98	27
5	4.0	8.1	0.50	0.78	28
6	4.0	8.2	0.25	1.4	28
7	4.0	8.2	0.75	1.6	29
8	4.0	8.2	0.31	1.1	30
9	4.0	8.2	0.79	0.39	25
10	4.0	8.3	0.31	1.2	29
11	4.0	8.4	0.54	0.61	28
Average	3.5 ± 0.7	8.1 ± 0.1	0.54 ± 0.16	0.96 ± 0.23	29 ± 1

\*14-Day average values before nitrification occurrence.

### Logistic regression models

Table 6 shows logistic regression results of the single-factor Type I models. The positive  $\beta_1$  for total chlorine residual indicated that the possibility of avoiding nitrification increased or the risk of nitrification occurrence decreased as total chlorine residual increased, while the negative  $\beta_1$  for temperature and nominal detention time meant that the possibility of avoiding nitrification decreased as these two factors increased. The  $P$  value of 0.64 for the linear form “pH” in Model 1a shows that this linear function form was not significant at the 0.1 level. An alternative form of  $(pH - pH_{opt})^2$  in Model 1b was estimated to be significant at the 0.1 level when  $pH_{opt} = 8.3$ . Model 1b had higher concordant and lower AIC values, which suggests that Model 1b was superior to Model 1a for estimating pH effects on the risk of nitrification occurrence. The risk of nitrification occurrence appeared to peak at around pH 8.3 instead of increasing or decreasing monotonically with pH.

In Table 6, the  $P$ -values for  $\beta_1$  show that temperature, total chlorine residual, and nominal detention time were significant contributors to the risk of nitrification occurrence in the pilot-scale systems, as expected. Free ammonia concentration was not estimated to be a significant contributor. As noted earlier, this might be due to the relatively high free ammonia concentrations (average about 0.85 mg NH<sub>3</sub>-N/L) in the pilot-scale systems. The presence of ammonia is essential for AOB growth to occur, but the concentration of ammonia was not a major factor limiting growth, and thus, small changes in ammonia concentration would not prompt or delay nitrification occurrence significantly.

Table 7 shows the logistic regression results of the Type II model, which included the summation of multiple factors. Factors including  $(pH - pH_{opt})^2$ , temperature, and total chlorine residual were estimated to be significant contributors, which was consistent with results estimated from the Type I models. The positive  $\beta_1$  for  $(pH - pH_{opt})^2$  and total

**Table 5** | Summary of conditions in reactors that did not undergo nitrification

ID	$\tau$ (day)	pH			Total chlorine (mg Cl <sub>2</sub> /L)		Free ammonia (mg NH <sub>3</sub> -N/L)		Temperature (°C)	
		Average pH $\pm$ 95% confidence	Minimum 14-day average	Maximum 14-day average	Minimum 14-day average	Maximum 14-day average	Minimum 14-day average	Maximum 14-day average	Minimum 14-day average	Maximum 14-day average
1	1.0	6.5 $\pm$ 0.5	4.8	7.8	0.045	4.2	0.16	2.2	24	30
2	1.0	6.5 $\pm$ 0.5	4.7	7.8	0.10	6.2	0.15	1.7	25	32
3	1.0	6.9 $\pm$ 0.4	5.2	8	0.50	3.2	0.26	1.2	17	35
4	1.0	7.0 $\pm$ 0.4	5.6	8.3	0.66	1.8	0.086	0.66	16	29
5	1.0	7.2 $\pm$ 0.4	5.8	8.1	1.1	4.8	0.050	2.7	16	30
6	1.0	7.4 $\pm$ 0.2	6.0	8.3	1.5	4.6	0.34	1.6	20	29
7	1.0	8.1 $\pm$ 0.1	7.9	8.4	1.0	5.2	0.31	1.4	20	31
8	1.0	8.1 $\pm$ 0.1	7.9	8.2	1.7	6.6	0.37	1.6	21	32
9	1.0	8.1 $\pm$ 0.1	7.8	8.2	1.2	6.4	0.13	2.1	21	31
10	1.0	8.1 $\pm$ 0.1	7.9	8.3	1.1	6.7	0.088	0.7	20	31
11	1.0	8.2 $\pm$ 0.1	8.0	8.5	0.5	3.5	0.13	1.4	19	30
12	1.0	8.2 $\pm$ 0.1	8.1	8.4	1.3	5.1	0.13	1.6	19	30
13	1.0	8.2 $\pm$ 0.1	8.0	8.3	1.0	4.8	0.083	0.58	21	31
14	1.0	8.3 $\pm$ 0.1	8.0	8.5	1.1	3.7	0.33	2.0	21	31
15	1.0	8.9 $\pm$ 0.2	8.3	9.6	0.97	3.0	0.23	1.6	23	30
16	1.0	9.0 $\pm$ 0.2	8.4	9.7	1.2	3.3	0.27	1.8	23	28
17	1.0	9.2 $\pm$ 0.2	8.8	10.2	0.36	2.5	0.29	2.0	21	28
18	1.0	9.5 $\pm$ 0.2	8.9	9.9	0.20	4.4	0.38	1.0	20	27
19	1.0	9.5 $\pm$ 0.2	8.8	10.1	0.23	3.8	0.18	0.94	20	29
20	1.0	9.6 $\pm$ 0.2	8.8	10.5	0.53	3.8	0.43	2.3	23	29
21	4.0	6.5 $\pm$ 0.5	4.1	7.9	0	2.8	0.033	1.3	22	29

Table 5 | (continued)

ID	$\tau$ (day)	Average pH $\pm$ 95% confidence	pH		Total chlorine (mg Cl <sub>2</sub> /L)		Free ammonia (mg NH <sub>3</sub> -N/L)		Temperature (°C)	
			Minimum 14-day average	Maximum 14-day average	Minimum 14-day average	Maximum 14-day average	Minimum 14-day average	Maximum 14-day average	Minimum 14-day average	Maximum 14-day average
22	4.0	6.8 $\pm$ 0.4	4.8	7.9	0.02	2.6	0.13	2.3	23	29
23	4.0	7.4 $\pm$ 0.3	5.1	8.1	0.12	1.6	0.25	1.0	17	29
24	4.0	7.7 $\pm$ 0.1	6.3	8.4	0.27	2.9	0.3	2.3	19	30
25	4.0	8.3 $\pm$ 0.1	8.1	8.4	0.60	3.1	0.38	2.4	21	30
26	4.0	8.3 $\pm$ 0.1	8.0	8.4	0.40	3.2	0.22	1.9	21	31
27	4.0	8.3 $\pm$ 0.1	8.1	8.4	0.40	5.4	0.14	1.3	20	31
28	4.0	8.7 $\pm$ 0.1	8.2	9.1	0.80	3.3	0.47	1.1	21	28
29	4.0	9.0 $\pm$ 0.2	8.5	9.5	1.2	3.5	0.38	1.4	23	28
30	4.0	9.1 $\pm$ 0.2	8.7	9.8	0.20	2.5	0.33	1.9	21	28
31	4.0	9.2 $\pm$ 0.1	8.8	9.5	0.25	3.1	0.4	0.73	21	27
32	4.0	9.3 $\pm$ 0.1	8.9	9.7	0.16	2.8	0.31	0.98	21	28
33	4.0	9.4 $\pm$ 0.2	8.8	9.9	0.57	2.6	0.54	2.4	21	28

**Table 6** | Logistic regression of type I models

Model	Factors ( $X_1$ )	$\beta_0$	P-value for $\beta_0$	$\beta_1$	P-value for $\beta_1$	Model $\chi^2$ [df, P]	Concordant (%)	AIC
1a	<i>pH</i>	2.1	0.36	0.13	0.64	0.22 [1, 0.64]	50	96
1b	$(pH - pH_{opt})^2$	2.3*	<0.0001	4.0*	0.091	12 [1, 0.0006]	71	85
1c	<i>T</i> (°C)	11*	0.0002	-0.30*	0.0040	10 [1, 0.0013]	76	86
1d	$C_d$ (mg $Cl_2/L$ )	1.4*	0.0031	1.7*	0.0063	18 [1, <1e-4]	78	83
1e	$\tau$ (day)	5.0*	<0.0001	-0.65*	0.015	8.0 [1, 0.0047]	50	88
1f	$C_s$ (mg N/L)	3.5*	<0.0001	-0.34	0.51	0.42 [1, 0.52]	57	96

\*Coefficient that is statistically significant at the  $P = 0.1$  level.

chlorine residual indicated that the possibility of avoiding nitrification increased or the risk of nitrification occurrence decreased as these two factors increased. The negative  $\beta_1$  for temperature meant that the possibility of avoiding nitrification decreased as this factor increased. However, nominal detention time was not estimated to be a significant contributor to nitrification occurrence in the Type II model. This may be due to the correlation between nominal detention time and total chlorine residual ( $r = -0.31$ ).

After eliminating terms in the original Type II model that were estimated to be insignificant at the 0.1 level, the simplified Type II model was estimated to be significant with a  $P$  value less than  $10^{-4}$  and a  $\chi^2$  of 53 (critical value of 6.3 at 0.1 level [df = 3]). The model performance was significantly improved with a concordant of 98%. When compared with the single-factor Type I models with concordant values ranging from 50% to 78%, none of the models predicted as accurately as the simplified Type II model. The smaller AIC value of the simplified Type II model also shows that this model was superior to any single-factor Type I model. These results indicate that all significant contributors significantly affected the risk of nitrification occurrence in the pilot-scale systems and no single contributor appeared to be dominant. To accurately predict risk of nitrification occurrence requires summing the contributions from pH, temperature, and total chlorine residual.

The original Type III model included the factors that were estimated to be significant at the 0.1 level in the Type I models and the interactions of these factors with total chlorine residual. As shown in Table 7, the interaction of  $C_d$

and pH was the only significant interaction at the 0.1 level in terms of contribution to nitrification occurrence. Nominal detention time, the interaction of  $\tau C_d$ , and the interaction of  $TC_d$  were estimated to be insignificant and were eliminated from the original Type III model. The simplified Type III model showed that the three significant contributors from the Type II model were significant at the 0.1 level together with the interaction between pH and total chlorine residual. Overall, the significance and accuracy of the simplified Type III model was similar to that of the simplified Type II model based on the model  $\chi^2$ , concordant, and AIC.

Both the simplified Type II model and the simplified Type III model were validated with 264 ( $33 \times 8$ ) randomly selected conditions from reactors that did not undergo nitrification. Both models correctly predicted no nitrification occurrence in 99% of the conditions tested. However, the simplified Type II model was selected as the logistic model to predict the risk of nitrification occurrence in the pilot-scale systems. Of the three models studied, this model had the least degrees of freedom and the best performance in terms of concordant and AIC.

After the simplified Type II model was selected as the prediction model, the optimum pH for nitrification occurrence ( $pH_{opt}$ ) was estimated to be 8.3 by the cross-validation method. As shown in Figure 4, the simplified Type II model predicts the risk of nitrification occurrence in the pilot-scale systems with the highest concordant and the lowest AIC values when pH = 8.3. This value is comparable to previously reported values of about 8.5 (Harrington *et al.* 2002).

**Table 7** | Logistic regression of the type II model and the type III model

Factors	Type II model				Type III model			
	Original		Simplified*		Original		Simplified*	
	$\beta$	P	$\beta$	P	$\beta$	P	$\beta$	P
Intercept	13	0.011	13	0.011	2.8	0.79	10 <sup>†</sup>	0.037
( $pH - pH_{opt}$ ) <sup>‡</sup>	6.0 <sup>†</sup>	0.089	5.9 <sup>†</sup>	0.085	12 <sup>†</sup>	0.047	9.4 <sup>†</sup>	0.050
T (°C)	-0.51 <sup>†</sup>	0.0064	-0.49 <sup>†</sup>	0.0054	-0.22	0.49	-0.42 <sup>†</sup>	0.016
C <sub>d</sub> (mg Cl <sub>2</sub> /L)	2.3 <sup>†</sup>	0.0055	2.5 <sup>†</sup>	0.0017	-42	0.14	-27 <sup>†</sup>	0.084
$\tau$ (day)	-0.19	0.58			0.49	0.41		
C <sub>s</sub> (mg N/L)	0.49	0.64						
pH C <sub>d</sub>					6.8	0.12	3.6 <sup>†</sup>	0.066
T C <sub>d</sub>					-0.30	0.45		
$\tau$ C <sub>d</sub>					-0.85	0.34		
Model $\chi^2$ [df, P]	53 [5, <0.0001]		53 [3, <0.0001]		57 [7, <0.0001]		55 [4, <0.0001]	
Concordant (%)	98		98		98		98	
AIC	51		47		51		47	
Validation (%) <sup>‡</sup>	99		99		99		99	

\*A simplified model only includes parameters that are statistically significant at the  $P = 0.1$  level.

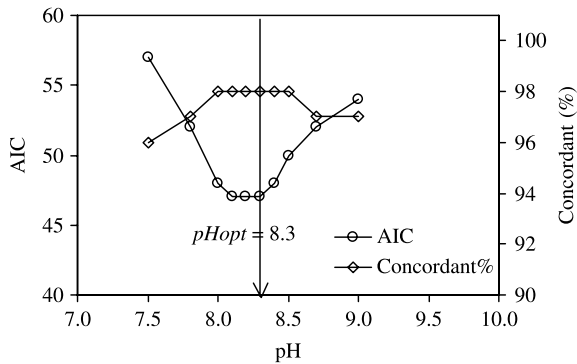
<sup>†</sup>Coefficient that is statistically significant at the  $P = 0.1$  level.

<sup>‡</sup>The percentage of correct predictions of nitrification occurrence verified with random-selected conditions in reactors that did not undergo nitrification.

Figure 5 shows the probability  $p$  of nitrification prevention in the pilot-scale systems as predicted by the simplified Type II model. Three probability levels are plotted in Figure 5a. Curves for the probability levels of  $p = 0.99$  and  $p = 0.90$  show the conditions for which nitrification would be prevented 99% and 90% of the time, respectively. Curves for the probability levels of  $p = 0.99$  and  $p = 0.90$  also show the conditions for which there are 1% and 10% nitrification occurrence risks, respectively. When  $p = 0.50$ , a reactor has an equal risk of having or not having nitrification. Two temperature levels, 25 and 30°C, were selected for illustration in Figure 5b. For comparison, the 14-day average temperatures before nitrification ranged from 25 to 32°C with an average of 29°C in the pilot-scale systems.

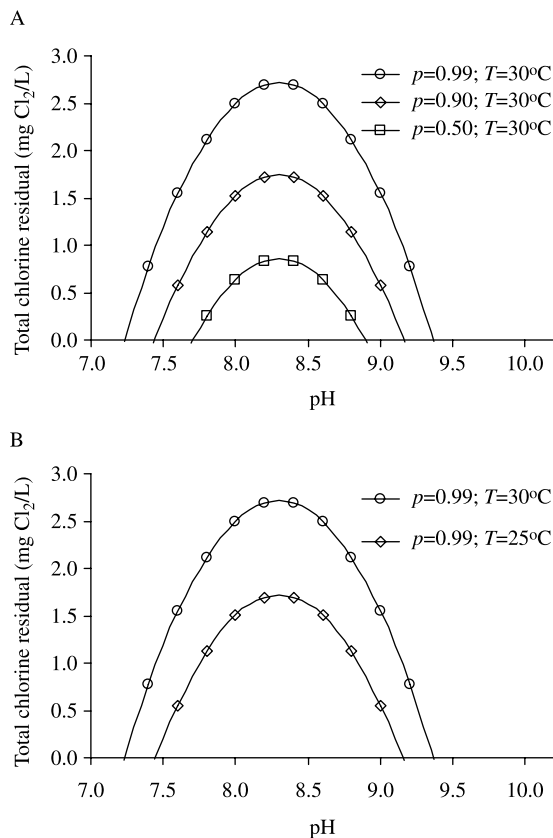
As shown in Figure 5a, our system had a 99% probability of avoiding nitrification when the system was operated at 30°C and at pH values and chlorine residuals on the  $p = 0.99$  curve (circles). As the pH in the system moves away from the optimum pH of 8.3 in either direction, less chlorine residual is required for nitrification prevention. For example, a chlorine residual about 2.6 mg Cl<sub>2</sub>/L would prevent nitrification 99% of the time at 30°C and pH 8.5. This residual would decrease to 1.5 mg Cl<sub>2</sub>/L when pH increased to 9.0. All points below the  $p = 0.50$  curve (squares) in Figure 5a suggest inadequate chlorine residuals and that nitrification would occur more than 50% of the time at 30°C. Figure 5b shows that less chlorine residual is required to prevent nitrification when the temperature





**Figure 4** | The optimum pH for nitrification occurrence estimated by cross-validation of the simplified Type II model.

decreases. For example, a chlorine residual about 2.6 mg  $\text{Cl}_2/\text{L}$  would prevent nitrification 99% of the time at 30°C and pH 8.5. When temperature decreases to 25°C, the residual required to achieve the same nitrification risk decreases to 1.5 mg  $\text{Cl}_2/\text{L}$ .



**Figure 5** | Probability of preventing nitrification occurrence in the pilot-scale systems predicted by the simplified Type II model.

In summary, based on nitrification occurrence observed in the pilot-scale systems, the Type II model was used to quantify the contribution from pH and other factors to the risk of nitrification occurrence in the pilot-scale systems. When applied to other pilot-scale or full-scale distribution systems, the logistic model can be adapted to their in-situ environmental conditions, operational parameters, and historical nitrification occurrence data. After regression analysis, it is likely that the parameter estimates or the function formats of the model will be different for different systems. However, once the model is developed, it can serve as an easy-to-use tool for the drinking water utility to determine which operational parameter should be controlled, and more importantly, to what degree the controlling practice should be applied to effectively decrease the risk of nitrification occurrence in their systems. For example, under conditions observed in this study, as shown in Table 3, the developed logistic model suggests that controlling pH and chlorine residual are more effective than controlling free ammonia levels to decrease the risk of nitrification in our pilot-scale systems.

## CONCLUSIONS

1. Nominal detention time (1–4 days) and pH (4.1–10.5) were observed to have significant impacts on nitrification occurrence in pilot-scale systems, which exhibited preference for a warmer temperature (25–30°C) and lower chlorine residual (<1.0 mg  $\text{Cl}_2/\text{L}$ ).
2. Total chlorine residual, pH, temperature, and nominal detention time were estimated to be significant contributors to the possibility of avoiding nitrification (or the risk of nitrification occurrence) in the pilot-scale systems. Although the presence of ammonia is essential for nitrification, free ammonia concentration was not estimated to be significant within the studied range of 0.030 to 2.7 mg  $\text{NH}_3\text{-N}/\text{L}$ , possibly due to observed free ammonia concentrations that were higher than the half saturation constant. The risk of nitrification occurrence was estimated to be greatest at pH 8.3. The interaction of pH with total chlorine residual was estimated to be

statistically significant at the 0.1 level in terms of the contribution to the risk of nitrification occurrence.

- None of the significant contributors appeared to be dominant on predicting the risk of nitrification occurrence. A simplified logistic model was able to predict the risk of nitrification occurrence in the pilot-scale systems based on a combination of pH, temperature, and total chlorine residual. Nominal detention time was not needed in the model when total chlorine residual was included because these two factors had a weak correlation with each other in the systems.

## ACKNOWLEDGEMENTS

Support for this research was provided by the National Science Foundation (BES-0112128), Wisconsin Department of Natural Resources, the University of Wisconsin-Madison Graduate School, and the University of Wisconsin-Madison Institute for Environmental Studies. During this study, Jian Yang was a graduate student at the University of Wisconsin-Madison.

## REFERENCES

- AWWA 2000 Committee report: disinfection at large and medium size systems. *J. AWWA* **92**, 32–43.
- AWWA and AWWARF 1992 *Water Industry Database: Utility Profiles*. AWWA, Denver, CO.
- AWWA, EES (Economic and Engr. Services, Inc.) 2000 *M/DBP FACA Support Document* ([www.epa.gov/safewater/tcr/pdf/nitrification.pdf](http://www.epa.gov/safewater/tcr/pdf/nitrification.pdf)), USEPA.
- Bowie, G. L., Mills, W. B., Porcella, D. B., Campbell, C. L., Pagenkopf, J. R., Rupp, G. L., Johnson, K. M., Chan, P. W. H. & Cherini, S. A. 1985 *Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling*. 2nd edition. EPA/600/3-85/040, Environmental Research Laboratory, USEPA.
- Cunliffe, D. A. 1991 Bacterial nitrification in chloraminated water supplies. *App. Environ. Micro.* **57**(11), 3399–3402.
- Fleming, K. K., Harrington, G. W. & Noguera, D. R. 2005 Nitrification control curves: a new strategy for nitrification prevention. *J. AWWA* **97**(8), 90–99.
- Gale, P., Lacey, R., Stanfield, G. & Holt, D. 1997 The development and application of coliform predictive models for the UK water industry. *J. Water Sci. Res. Technol.-Aqua*. **46**(4), 185–195.
- Grady, C. P. L. Jr. & Lim, H. C. 1980 *Biological Wastewater Treatment*. Marcel Dekker, New York.
- Harrington, G. W., Noguera, D. R., Kandou, A. I. & Vanhoven, D. J. 2002 Pilot-scale evaluation of nitrification control strategies. *J. AWWA* **94**(11), 78–89.
- Harrington, G. W., Noguera, D. R., Bone, C. C., Kandou, A. I., Oldenburg, P. S., Regan, J. M. & VanHoven, D. 2003 *Ammonia Release from Chloramine Decay: Implications for the Prevention and Control of Nitrification in Drinking Water Distribution Systems*. Final Rept. AWWARF, Denver, CO.
- Holt, J. G., Krieg, N. R., Sneath, P. H. A., Staley, J. T. & Williams, S. T. 2000 Aerobic chemolithotrophic bacteria and associated organisms. In: Hensyl, W. R. (ed.) *Bergey's Manual of Determinative Bacteriology*, 9th Edition. Lippincott Williams and Wilkins Publishers, Philadelphia, PA.
- Hosmer, D. W. & Lemeshow, S. 2000 *Applied Logistic Regression*, 2nd Edition. Wiley Series in Probability and Statistics, New York.
- Kirmeyer, G. J., Odell, L. H., Jacangelo, J., Wilczak, A. & Wolfe, R. L. 1995 *Nitrification Occurrence and Control in Chloraminated Water Systems*. AWWARF and AWWA, Denver, CO.
- Lieu, N. I., Wolfe, R. L. & Means, E. G. 1993 Optimizing chloramine disinfection for the control of nitrification. *J. AWWA* **85**(2), 84–90.
- Lipponen, M. T. T., Suutari, M. H. & Martikainen, P. J. 2002 Occurrence of nitrifying bacteria and nitrification in Finnish drinking water distribution systems. *Water Res.* **36**, 4319–4329.
- Liu, S., Taylor, J. S., Randall, A. A. & Dietz, J. D. 2005 Nitrification modeling in chloraminated distribution systems. *J. AWWA* **97**(10), 98–108.
- Oldenburg, P. S., Regan, J. M., Harrington, G. W. & Noguera, D. R. 2002 Kinetics of *Nitrosomonas europaea* inactivation by chloramine. *J. AWWA* **94**(10), 100–110.
- Odell, L. H., Kirmeyer, G. J., Wilczak, A., Jacangelo, J. G., Marcinko, J. P. & Wolfe, R. L. 1996 Controlling nitrification in chloraminated systems. *J. AWWA* **88**(7), 86–98.
- Park, H. D. & Noguera, D. R. 2007. Characterization of two ammonia-oxidizing bacteria isolated from reactors operated with low dissolved oxygen concentrations. *J. Appl. Microbiol.* **102**(5), 1401–1417.
- Regan, J. M., Harrington, G. W. & Noguera, D. R. 2002 *Ammonia- and nitrite-oxidizing bacterial communities in a pilot-scale chloraminated drinking water distribution system*. *App. Environ. Micro.* **68**(1), 73–81.
- Regan, J. M., Harrington, G. W., Baribeau, H., Leon, R. D. & Noguera, D. R. 2003 *Diversity of nitrifying bacteria in full-scale chloraminated distribution systems*. *Water Res.* **37**, 197–205.
- Rittmann, B. E. & McCarty, P. L. 2001 *Environmental Biotechnology: Principles and Applications*. McGraw-Hill Companies, Inc., New York.
- Skadsen, J. & Sanford, L. 1996 The effectiveness of high pH for control of nitrification and the impact of ozone on nitrification control. In *Proc. 1996 AWWA Water Quality Tech. Conf.* Boston, MA.

- Standard Methods for the Examination of Water and Wastewater* 1998 20th edition, APHA, AWWA, and WEF, Washington, DC.
- USEPA 1989 National Primary Drinking Water Regulations; Filtration, Disinfection; Turbidity, Giardia Lamblia, Viruses, Legionella, and Heterotrophic Bacteria; Final Rule. *Fed. Reg.* 54: 124: 27486–27541.
- USEPA 1997 *Method for the Determination of Inorganic Anions in Water by Ion Chromatography*. EPA 600-R-98-118, Rev. 1.0, Washington, DC.
- Valentine, R. L., Ozekin, K. & Vikesland, P. J. 1998 *Chloramine Decomposition in Distribution System and Model Waters*. AWWARF and AWWA, Denver, CO.
- Volk, C. & Joret, J. C. 1994 Parameters predictifs de l'apparition des coliformes dans les reseaux de distribution d'eau d'alimentation. *Rev. Sci de l'Eau* 7, 145–166.
- Wilczak, A., Jacangelo, J. G., Marcinko, J. P., Odell, L. H., Kirmeyer, G. J. & Wolfe, R. L. 1996 Occurrence of nitrification in chloraminated distribution system. *J. AWWA* 88, 74–85.
- Wolfe, R. L., Lieu, N. I., Izaguirre, G. & Means, E. G. 1990 Ammonia-oxidizing bacteria in a chloraminated distribution system: seasonal occurrence, distribution, and disinfection resistance. *Appl. Environ. Microbiol.* 56(2), 451–462.
- Yang, J. 2005 *Nitrification Modeling in Pilot-Scale Chloraminated Drinking Water Distribution System*. PhD dissertation, University of Wisconsin-Madison, Department of Civil and Environmental Engineering, Madison, WI.
- Yoshioka, T., Terai, H. & Saijo, Y. 1982 Growth kinetic studies of nitrifying bacteria by the immunofluorescent counting method. *J. Gen. Appl. Microbiol.* 28, 169–180.

First received 17 April 2007; accepted in revised form 19 April 2007