

Design Model Parameter Analysis for Nitrifying Trickling Filters

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ABSTRACT: Nitrifying trickling filters (NTFs) represent an effective technology for water resource recovery facilities (WRRFs) to achieve compliance with ammonia-N permits. However, while the potential benefits of NTFs are many, the design methods and associated parameter databases are underdeveloped. Research herein focused on analysis of pilot-scale NTF data to develop enhanced design guidance. $r_{n(\max,0)}$ values ranged from 1.19–3.38 gN m⁻²d⁻¹, and correlated with influent ammonia-N concentration and loading. The transition concentration from $r_{n(\max,0)}$ ranged from 0.9–22.2 mgN/L, and correlated with ammonia-N loading. Zero-order nitrification ranging from 0.24–1.58 gN m⁻²d⁻¹ was observed down-gradient of $r_{n(\max,0)}$. First-order nitrification was not observed, nor was there a strong exponential correlation for decreasing nitrification rate. To translate results to NTF media different from that utilized, a relationship between the NTF media effectiveness parameter, E , and $r_{n(\max,0)}$ was established. Collectively, the data presented enhances the engineer's ability to model and design NTFs. *Water Environ. Res.*, **88**, 888 (2016).

KEYWORDS: nitrifying trickling filter, zero order nitrification, NTF media effectiveness parameter.

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Introduction

The discharge of excess ammonia-N into surface water bodies can create toxic conditions for certain aquatic organisms, and can also contribute to accelerated water body eutrophication. To minimize or avoid such conditions, municipal water resource recovery facilities (WRRFs), which are tasked with receiving and treating municipal wastewater, are realizing decreased effluent ammonia-N discharge limits (often to < 1–2 mgN/L; required effluent concentrations will vary depending on the receiving water body). In considering alternative WRRF configurations to remove ammonia-N (particularly for small communities), nitrifying trickling filters (NTFs) represent a simple operation and a potentially less costly technology as compared with conventional nitrifying activated sludge. However, while the potential benefits to NTFs are many (Daigger and Boltz, 2011), ultimately the guidance and criteria available to engineers for the design of full-scale NTFs remains underdeveloped, which could impair broader use of this treatment process.

Various theoretical and/or empirical models and approaches have been proposed for NTF design (e.g., USEPA, 1975; Gujer and Boller, 1986; Gullicks and Cleasby, 1986; Okey and Albertson, 1989; Parker et al., 1975, 1989; Rittmann and McCarty, 2001), some more sophisticated and fundamentally-

based than others. For example, at a fundamental level, Rittman and McCarty (2001) detail a steady-state, mass balance-based mechanistic model for biofilm reactors that integrates substrate flux with active biomass kinetics and stoichiometry, specifically at the biofilm level, to solve for effluent substrate concentrations from a TF. The more sophisticated, fundamental mechanistic approaches have greatly informed biofilm modeling and NTF design, although to employ such approaches for full-scale design and analysis requires more knowledge on process kinetics and stoichiometry than is commonly available or readily obtainable. At a more applied, macro-level, research has demonstrated that NTFs can be modeled based on a straight-forward application of nitrification kinetics. Specifically, at high ammonia-N concentrations (suggested at > 3–4 mgN/L) the NTF nitrification rate, r_n , has been observed to be impacted largely by limited oxygen diffusion into the biofilm (Gullicks and Cleasby, 1986; Okey and Albertson, 1989; Parker et al., 1975), and nitrification can be modeled on a maximum zero order ammonia-N removal basis. As treatment occurs within the NTF and the ammonia-N concentration in bulk solution decreases, the nitrification rate can decrease associated with biofilm ammonia-N diffusion limitation (suggested to occur when the ammonia-N concentration decreases below 3–4 mgN/L). Equation 1, presented in a form proposed by Parker et al. (1989) but based on work by Gujer and Boller (1986), is the foundation for the empirical, kinetics-based NTF design approach. The equation includes an empirical parameter (k) to account for a decreasing nitrification rate with NTF depth. In addition to eq 1, Parker et al. (1989) proposed a relationship (eq 2) to relate the maximum rate of ammonia-N removal with the NTF media characteristics and associated surface oxygen transfer rate (through a lumped media effectiveness (E) parameter), such that research results could be extrapolated to different types of plastic NTF media.

$$r_n = r_{n(\max)} \left(\frac{N}{k_n + N} \right)^a e^{-kz} \quad (1)$$

$$r_{n(\max)} = \frac{E * r_{(O_2, \max)}}{4.3} \quad (2)$$

Parameters for eqs 1 and 2 are defined as follows.

r_n = nitrification rate at ammonia concentration N , gN m⁻²d⁻¹

$r_{n(\max)}$ = maximum nitrification rate at ammonia concentration N , gN m⁻²d⁻¹

$r_{(O_2, \max)}$ = maximum surface oxygen transfer rate for the NTF media, gO₂ m⁻²d⁻¹

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- N = bulk ammonia-nitrogen concentration in the NTF, mg/L
- K_n = pseudo half saturation coefficient, mg/L (suggested to range from 1.0 to 2.0 (Grady Jr. et al., 2011; Gujer and Boller, 1986; WEF, 2010; Parker et al., 1989))
- a = empirical parameter used to modify the nitrification rate with depth ($a=1.0$ according to Parker et al., 1989)
- k = empirical parameter describing the decrease in nitrification rate with depth, m^{-1} ,
- z = depth within the NTF (measured from the top), m, and
- E = dimensionless media effectiveness factor.

The value of $r_{(O_2, \max)}$ can be estimated using the Logan trickling filter model (Logan, 1993, 1995; Logan et al., 1987); Parker et al. (1995) presents some $r_{(O_2, \max)}$ values for cross-flow plastic media.

Leveraging eq 1, there are two distinct, yet somewhat different, modeling approaches (summarized in (WEF, 2010)): (i) the semi-empirical approach developed by Gujer and Boller (1986) as amended by Parker et al., 1989; and (ii) a more simplified zero/first order analysis developed by Okey and Albertson (WEF, 2010; Okey and Albertson, 1989). The former approach involves two design equations derived from eq 1 – one for $k > 0$ (i.e., nitrification rate decreasing in the NTF) and one for $k = 0$ (i.e., nitrification rate constant in the NTF), with $a = 1.0$ in both cases. Application of the latter approach assumes zero-order nitrification prevails to a concentration of approximately 3–5 mgN/L, with a reduced nitrification rate (essentially first order) realized thereafter and down to the target effluent ammonia-N concentration ($a = 0.75$; the exponent aspect of eq 1 excluded).

While the empirical modeling and design of NTFs is relatively straight-forward, applying either approach described above ultimately demands knowledge on NTF kinetics and the associated empirical parameters. In this regard, some quality empirical data sets from pilot and/or full scale operations are available (e.g., (Andersson et al., 1994; Boller and Gujer, 1986; Coats et al., 2015; Goldstein and Smith, 2002; Gullicks and Cleasby, 1986; Mofokeng et al., 2009; Parker et al., 1989, 1997, 1995)). However, of the data sets available in the peer-reviewed literature and design manuals, only those published by Parker and coworkers, and Coats et al. (2015), include data on internal NTF kinetics, as compared with the more common “apparent” nitrification rates that only reflect NTF influent/effluent ammonia-N. Ultimately, design engineers need kinetic data internal to the NTF, not just “apparent” rate data, to apply the design models based on eqs 1 and 2. The value and importance of such data within the depths of an NTF relates to the ability to refine and optimize the empirical-based design of full-scale NTFs for site-specific conditions.

The city of Colfax, located in southeastern Washington State, operates an aerated lagoon WRRF to produce reclaimed water in compliance with its state-issued National Pollutant Discharge Elimination System (NPDES) permit, which is focused on the removal of BOD and total suspended solids (TSS). However, a pending water quality assessment of the receiving water could add ammonia-N limits to Colfax’s permit. Considering the excess BOD removal capacity of the existing lagoon system, the

city recognized that an NTF would be a potentially significant cost-saving alternative to lagoon demolition and an activated sludge WRRF upgrade. The city thus commissioned an extended pilot-scale NTF study at their WRRF site, with the purpose to confirm for both the city and the state regulatory authority the ability of an NTF to produce reclaimed water at or below potential future NH_3 limits, while also generating important design data. Coats et al. (2015) published a detailed study on the four-year performance of the pilot NTF treating the lagoon effluent, which demonstrated the ability of this technology to achieve desired effluent criteria. As a follow-up to the original investigation, this manuscript focuses on an interrogation of the design method and associated kinetic parameters (integrating peer reviewed literature data) to produce additional process data and guidance to support use of eqs 1 and 2 in the modeling and design of full-scale NTFs.

Materials and Methods

Description of the Colfax, WA, WRRF. Colfax owns and operates a system to receive and treat wastewater derived from residential, commercial, and industrial services located within the city limit. Two aerated lagoons, operated in series, form the central biological treatment system, targeting the removal of BOD and TSS. Additional WRRF details are provided in Coats et al. (2015).

NTF Design and Construction. The pilot NTF was designed to receive approximately 5% of the city’s average influent wastewater flow; the resulting design flow rate was 2.84 m^3/h (12.5 gal/min). On an ammonia-N basis, the pilot system was designed to treat an influent maximum concentration of 25 mgN/L. Additional details on the original pilot system design are presented in Coats et al. (2015).

The plastic media selected for the NTF was model CF-1900 manufactured by Brentwood Industries (Reading, PA, USA), which provided a specific surface area of 157 m^2/m^3 (48.0 ft^2/ft^3). The CF-1900 is manufactured in 0.61m \times 0.61m \times 1.22m (2ft \times 2ft \times 4ft) blocks; the pilot NTF plan view cross section was established as 1.22m \times 1.22m (4ft \times 4ft). Based on the design hydraulic and ammonia-N loading, and following accepted NTF design standards (Tchobanoglous et al., 2014), the required total NTF volume was estimated at 7.1 m^3 (250 ft^3), yielding a total height of 4.88 m (16ft). Two NTFs in series, each 2.44 m (8ft) tall were constructed (with 1.91 cm thick plywood walls), and a total of 16 media modules were required. The resulting surface area-to-height ratio was 0.6 m^2/m . The design hydraulic loading rate (HLR = 1.91 m/h, based on gross plan view area) was at the low end operating range according to the manufacturer’s guidance. The specific hydraulic loading rate (sHLR; based on total media surface area) was 0.0025 m/h; the sHLR was similar to the volumetric loading parameter (Rittmann and McCarty, 2001), but incorporates media surface area. Lagoon 2 effluent is pumped from the settling tube module to the NTFs using 0.373 kW (0.5 hp) sump pumps (Liberty Pumps, Bergen, NY, USA); each NTF is supplied by a single pump. The pilot NTF utilized a tipping bucket to distribute influent over the media, with 50% of the NTF surface area dosed for each “tip.” This dosing mechanism pulsed large volumes of influent wastewater to the NTF, thereby enhancing excess biofilm sloughing; both Albertson (1995) and Parker et al. (1989) raised the concern of excess biofilm accumulation, and suggested a large hydraulic pulse to remedy the problem. The operating dosing rate for the flow rates

Table 1—Summary of NTF Operational Criteria.

Year and Operational Period (Y: M/D-M/D) ¹	Average Flow Rate \pm SD m ³ /h (gal/min)	Average HLR ² m/h (gal/d/(ft ²))	Average sHLR ³ m/h (gal/d/(ft ²))	Average NH ₃ Loading Rate gN/m ² -d \pm std. dev. ⁴ (max/min)	
				NTF1	NTF2
Original Design	2.84 (12.5)	1.91 (1125)	0.0025 (1.46)	1.5 ⁵	
1: 6/1–8/3	2.84 (12.5)	1.91 (1125)	0.0025 (1.46)	1.3 \pm 0.8 (3.2/0.6)	0.8 \pm 1.2 (3.3/0)
2: 5/18–9/29	7.74 (34.1)	5.20 (3069)	0.0068 (4.0)	6.8 \pm 2.3 (12.6/1.1)	3.3 \pm 2.6 (9.9/0.1)
3: 2/29–4/4	3.11 (13.7)	2.09 (1233)	0.0027 (1.61)	1.6 \pm 0.4 (2.9/0.7)	0.6 \pm 0.4 (2.7/0)
4: 2/26–6/6	3.31 (14.6)	2.22 (1314)	0.0029 (1.71)	3.1 \pm 0.5 (4/2)	2.1 \pm 0.7 (3.3/0.5)
5: 3/29–8/20 (NTF1)	2.5 \pm 0.46 (11 \pm 2)	1.68 (990)	0.0044 (2.58)	2.3 \pm 0.4 (3.8/0.9)	–
5: 2/20–8/20 (NTF2)	3.07 \pm 0.49 (13.5 \pm 2.2)	2.07 (1217)	0.0054 (3.17)	–	2.8 \pm 0.5 (4.3/1.3)

¹ Years 1–4 from Coats et al. (2015); both NTFs were operated in series. For Year 5 (this follow-up study), the NTFs were operated independently.

² calculated as Flow Rate divided by NTF plan view surface area.

³ calculated as Flow Rate divided by actual NTF media surface area (Y1–4, NTFs operated in series; Y5, NTFs operated independently).

⁴ Based on total media surface area.

⁵ Based on both NTFs operated in series.

evaluated in this follow-up study ranged from 10–16 and 6–10 mm per tip (NTF1 and NTF2, respectively), sufficient to prevent excess biofilm accumulation. A perforated trough system was constructed below the tipping bucket and over the top of the NTF media to promote uniform hydraulic distribution across the media. To ensure that oxygen would not be a limiting nutrient, each NTF was fitted with a blower (0.16 m³/min (5.6 ft³/min) capacity) mounted at the base of the NTF in the annular space below the media; regular DO measurements of NTF1 effluent confirmed that the residual dissolved oxygen consistently exceeded 5 mg/L (Lagoon 2, which was aerated, exhibited a dissolved oxygen concentration exceeding 1 mg/L). To facilitate nitrification kinetic analysis within the NTFs, three 5cm (2 in) diameter sampling holes were drilled across one side of each NTF tower at media heights of 30, 61, 91, 122, 152, 182, and 213 cm (12, 24, 36, 48, 60, 72, and 84 in) measured from the top of the tower.

NTF Operation. In the first study (Coats et al., 2015) the NTF system was operated in series and during the late winter/early spring into summer months over a period of four years. Results from this follow-up study are from year 5 operations (Table 1), wherein the two NTFs were operated independently, with the goal to obtain an enhanced set of kinetic data. Water samples were regularly collected at four locations: influent and effluent to NTF1 and NTF2. Additional samples were collected intermittently within the NTF for a more detailed kinetics analysis. Temperature in the lagoon was continuously monitored using a Hobo Water Temp Pro v2 data logger (Onset Computer Corporation, Bourne, MA, USA). Dissolved oxygen and pH were periodically measured in the lagoon and in each NTF effluent. Note that ultimately the city's lagoons began nitrifying (as was experienced during all four years of the original study (Coats et al., 2015)), requiring the addition of anhydrous ammonia to sustain NTF operations (addition commencing on day 102).

Analytical Techniques. The ammonia-salicylate method was employed to quantify ammonia-N in the water samples, and two instruments were used to conduct the ammonia-N testing. A Lachat QuikChem AE Flow Injection Analyzer (Hach Co., Loveland, CO, USA) was used for some samples, following Lachat method 12-107-06-2-A. The instrument was set to measure the absorbance of the reacted sample at a wavelength of

660 nm. In addition, some samples were processed using Hach method 10031 (Loveland, CO, USA). A Spectronic® 20 Genesys™ spectrophotometer (Thermo-Fisher Scientific Corp, Waltham, MA, USA) was utilized to measure the absorbance of the reacted sample at a wavelength of 655 nm for ammonia-N. In all cases, ammonia-N concentrations were determined utilizing a standard curve ($R^2 > 0.99$). Split samples were processed through both instruments to ensure repeatability.

Results and Discussion

NTF Performance. One goal of the year 5 pilot scale testing was to evaluate the relative impact of lagoon influent water temperature on the establishment of the NTF flora and associated ammonia-N removal; from a permit perspective, the city would likely not need to remove ammonia-N during the winter months, but would need to be operational by April or May. Operational criteria are summarized in Table 1, and NTF performance is illustrated in Figure 1. NTF2 operations commenced February 27, while NTF1 operations commenced March 29. For NTF2, the nitrifying consortium did not establish until day 44 (April 12; influent water temperature $> 14^\circ\text{C}$; Figure 2), when a percent removal of 28% was recorded (treatment performance prior to that date was generally lower, and much more variable). In contrast, NTF1 began achieving a similar magnitude of treatment (36% removal) on operational day 59 (April 27, or only 27 days after NTF1 operations commenced; influent water temperature $> 12^\circ\text{C}$; Figure 2). Moreover, for both NTFs, treatment performance began to substantially improve after the water temperature was consistently exceeding 14°C (day 60). Once the nitrifying consortia established, NTF2 produced an average effluent concentration of $10.9 \pm 4.1 \text{ mgNH}_3\text{-N/L}$ (50.4% removal; $n = 52$), while NTF1 produced an average effluent concentration of $9.0 \pm 4.1 \text{ mgNH}_3\text{-N/L}$ (58.1% removal; $n = 46$). An F-test revealed that the two NTF effluent data sets had equal variance ($P = 0.44$), but that the two data set means were statistically different ($P = 0.022$). Ultimately, performance of the two pilot NTFs in Year 5 was comparable to that realized in Years 1–4 (Coats et al., 2015); while effluent ammonia-N concentrations were higher than anticipated for a future NPDES permit, the NTFs were operated at an NH₃ loading rate of approximately 52% (NTF1) and 91% (NTF2) greater than the original design condition

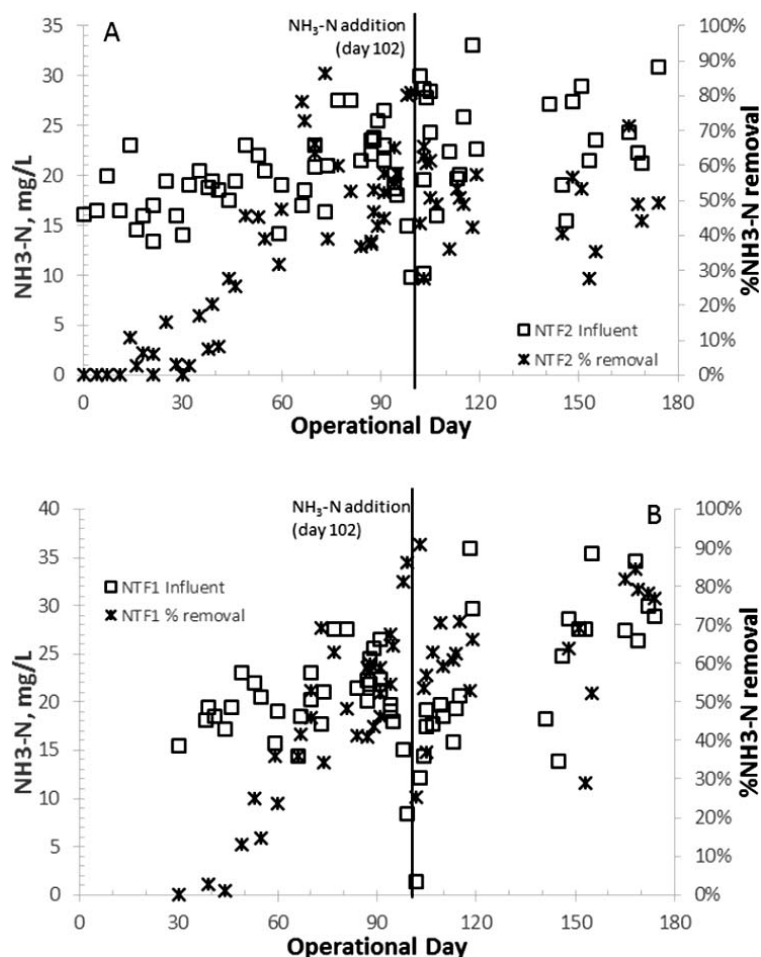


Figure 1—Ammonia removal performance summary (influent NH₃-N concentration; percent removal) for NTF2 (A) and NTF1 (B).

(Table 1). The NTFs were purposefully operated at higher ammonia-N loading, and independently, to facilitate the expanded kinetic assessments that were a principal goal of this Y5 study.

NTF Design and Nitrification Kinetics. Designing a full-scale NTF demands that engineers make two decisions: first, a modeling approach must be selected, and second, the design nitrification rate(s) must be established. Regarding NTF

modeling, as discussed, consensus in the prominent design manuals (Grady Jr. et al., 2011; WEF, 2010; Tchobanoglous et al., 2014) has adopted a largely empirical, kinetics-based NTF design approach. The two NTF design methods differ, in that the Gujer and Boller model (1986) is more grounded in theory and is somewhat more involved than that of Albertson and Okey (1989), which is a more simplified approach. However, as an example of the relative consistency between the two methods, in a re-analysis of this study's pilot NTF, while results for the different kinetic regimes differed slightly, the overall redesign remained the same (Coats et al., 2015); Wall et al. (2002) presented similar findings. Regardless of the design approach selected, though, selection of the NTF kinetic parameters – the critical decision by the engineer – remains the same.

Nitrification kinetics within NTFs have been the subject of detailed investigation and discussion over the years. Early research focused on “apparent” nitrification rates that only considered NTF influent/effluent ammonia-N (e.g., (Gullicks and Cleasby, 1986; Okey and Albertson, 1989)). Later research conducted a more in-depth evaluation of differential ammonia-N removal rates within the NTF (Andersson et al., 1994; Coats et al., 2015; Gujer and Boller, 1986; Parker et al., 1989, 1995). An excellent review on the evolution of investigating NTF nitrification kinetics is presented by Parker et al. (1989). As discussed herein, current modeling and design methods center

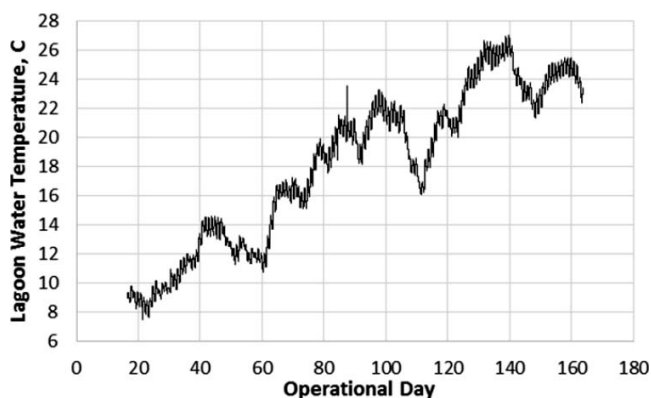


Figure 2—NTF influent water temperature.

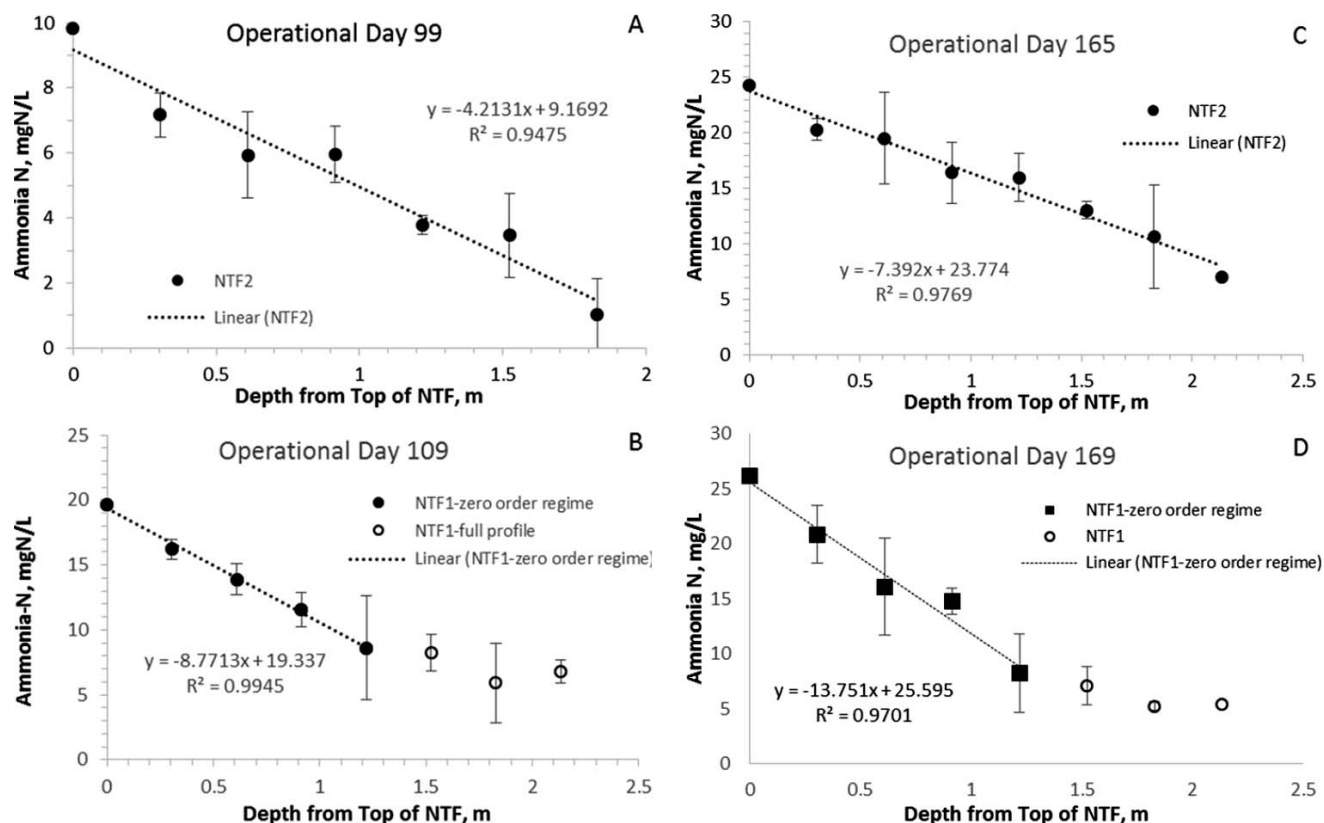


Figure 3—Example ammonia-N vs. depth plots for NTF2 (A), NTF1 (B), NTF2 (C), and NTF1 (D). Maximum zero order nitrification regimes are shown, along with the regression line and R^2 .

on the more detailed description of internal NTF kinetics. Gujer and Boller (1986), and later Parker et al. (1989), proposed that r_n be determined through assessing NH_3 removal in stages down an NTF tower, in order to properly extract kinetic parameters. In this regard, Parker et al. (1989), investigating a pilot-scale NTF, made two important observations regarding r_n : i) under conditions where the influent ammonia-N concentration is elevated such that ammonia-N loading remains high deep into the NTF, ammonia-N removal kinetics remain relatively constant throughout, however, ii) when the influent ammonia-N load is insufficient to maintain biofilm uniformity through the NTF, the nitrification rate will decrease with depth (Boller and Gujer, 1986; Parker et al., 1989). Observed decreases in nitrification rates with depth in the NTF have been associated with incomplete active biofilm development on the media due to variable ammonia-N loading (Gujer and Boller, 1986).

Based on a comprehensive review of past NTF research within the context of recommended NTF design practices, it is clear that design engineers could benefit from an expanded database, and clarification, of peer-reviewed nitrification kinetic data; the current database available in the peer-reviewed literature is limited. Thus, in this follow-up to our original pilot-scale NTF study (Coats et al., 2015), nitrification kinetics were more extensively investigated within the respective NTFs. For each NTF, water samples were collected at 21 different locations and at seven levels (plus influent/effluent) within the NTF (more sampling locations at increased depth resolution than the original study). Ammonia-N removal rates within the NTF were

evaluated, and maximum zero-order kinetic parameter ($r_{n(\max,0)}$) estimation was performed consistent with Tchobanoglous et al. (2014) based on the ammonia-N concentration gradients observed within the NTFs. Example plots of observed kinetics are shown in Figure 3 for both NTF1 and NTF2; as shown, depending on the NTF loading, there were occasions when only maximum zero-order nitrification was realized (i.e., Figures 3A and 3C). However, decreased nitrification rates (although not necessarily first order) were also observed (Figures 3B, 3D), generally consistent with that of Boller and Gujer (1986) and also with Parker et al. (1989). In total, 18 data sets were collected for NTF1 and NTF2, with kinetic parameters extrapolated; results are summarized in Table 2.

Calculated $r_{n(\max,0)}$ values were generally comparable to the $r_{n(\max)}$ values reported by Parker et al. (1989, 1999) who observed rates ranging from 2.1–3.2 $\text{gN m}^{-2}\text{d}^{-1}$ using similar cross-flow media. Compiling data from this and past studies, a correlation can be seen between $r_{n(\max,0)}$ and both influent ammonia-N concentration (Figure 4A) and influent ammonia-N load (Figure 4B); however, the correlation exhibits some variability, as indicated by the dashed lines. Note that the $r_{n(\max,0)}$ values were not corrected for temperature; ammonia-N removal kinetics (zero order) did not appear to be impacted by water temperature for this study nor for data mined from previous investigations (Figure 5). While in reality temperature most certainly would affect nitrification kinetics, the relative effect is likely masked by the gross calculation of $r_{n(\max,0)}$, and thus temperature effects cannot be discerned. In other words,

Table 2—Summary maximum nitrification rate and model analysis results for NTF performance.

Operational day	NTF	Influent $\text{NH}_3\text{-N}^1$			Effluent NH_3 , mgN/L	Water temp., °C	$r_{n(\max)}^2$ gN m ⁻² *d ⁻¹	$r_{n(\max,0)}^3$ gN m ⁻² *d ⁻¹	Empirical E ⁴		NH_3 at transition ⁵ , mgN/L
		mgN/L	kgN/d	gN m ⁻² *d ⁻¹					$r_{n(\max)}^1$	$r_{n(\max,0)}^2$	
99	1	8.4	0.58	1.02	0.9	21.7	1.58	1.23	0.54	0.42	0.9
109	1	19.7	1.0	1.75	6.8	17.7	2.46	1.91	0.84	0.65	8.6
119	1	23.2	1.5	2.63	9.7	21.6	3.21	3.38	1.10	1.16	8.0
145	1	16.0	0.82	1.44	0.02	22.8	3.80	2.90	1.30	0.99	3.4
155	1	35.4	1.79	3.14	16.9	24.3	3.47	3.04	1.19	1.04	22.2
165	1	27.4	1.36	2.38	5.0	22.9	3.60	3.04	1.23	1.04	9.6
168	1	34.6	1.6	2.80	5.3	23.0	6.82	3.54	2.34	1.21	11.6
169	1	26.1	1.31	2.30	5.5	22.7	3.73	2.95	1.28	1.01	8.2
172	1	29.9	1.56	2.73	6.45	22.7	4.82	3.30	1.65	1.13	11.2
174	1	28.9	1.37	2.40	6.73	22.6	5.57	2.65	1.91	0.91	11.3
109	2	9.8	0.65	1.14	1.3	21.7	2.46	1.19	0.84	0.41	1.3
129	2	22.6	1.49	2.61	9.6	21.6	2.61	1.63	0.89	0.56	12.9
145	2	21.9	1.63	2.86	11.3	22.8	3.90	2.83	1.34	0.97	16.5
155	2	23.5	1.65	2.89	15.2	24.3	3.88	1.90	1.33	0.65	15.2
165	2	24.3	1.71	3.00	7.0	22.9	3.90	2.96	1.34	1.01	7.0
168	2	22.3	1.58	2.77	11.4	23.0	3.27	2.24	1.12	0.77	14.6
169	2	21.0	1.43	2.51	11.9	22.7	2.80	2.63	0.96	0.90	12.4
174	2	30.9	2.17	3.80	15.7	22.6	4.05	2.51	1.39	0.86	17.0

¹ Unit loading (gN m⁻²*d⁻¹) based on actual NTF media surface area.

² Maximum ammonia removal rate constant, calculated within the top layer of the NTF.

³ Maximum zero-order ammonia removal rate constant, calculated within the NTF.

⁴ Media Effectiveness Factor (Parker et al., 1989); based on data from this study (see eq 2) and calculated based on an $r_{(\text{O}_2, \max)}$ of 12.55 gO₂/m²-d (estimated using the Logan trickling filter model (Logan, 1993, 1995; Logan et al., 1987)).

⁵ Transition from maximum zero-order nitrification.

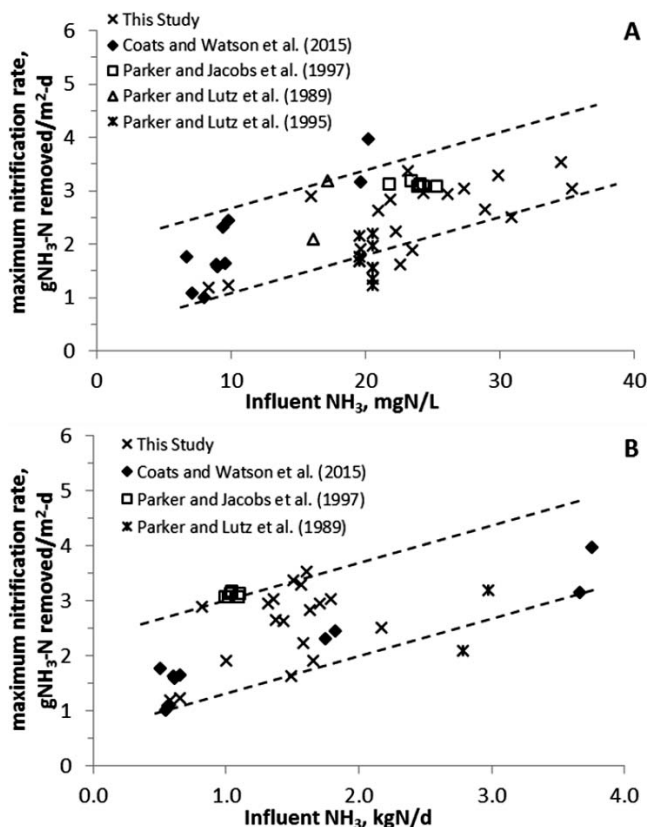


Figure 4—Graphical analysis and comparison of NTF maximum zero-order/maximum nitrification rates against (A) NTF influent ammonia (mgN/L) and (B) NTF ammonia-N loading (kgN/d).

$r_{n(\max,0)}$ is calculated based on total NTF media surface area, which does not necessarily reflect the actual mass of nitrifying biomass. Ultimately, the media effectiveness factor, E , better encapsulates the effect of temperature (and other operational variables), and this point is discussed later in this manuscript.

In considering selection of a design r_n value, beyond the data in Figure 4, a comprehensive review of the NTF literature revealed some important observations regarding estimation of the “maximum” rate of nitrification that would be used in NTF design. In contrast to the method employed herein and by Coats et al. (2015) to calculate $r_{n(\max,0)}$, research published by Parker and coworkers (Lutz et al., 1995; Parker et al., 1989, 1995, 1997) presents the nitrification rate calculated at the top layer of the

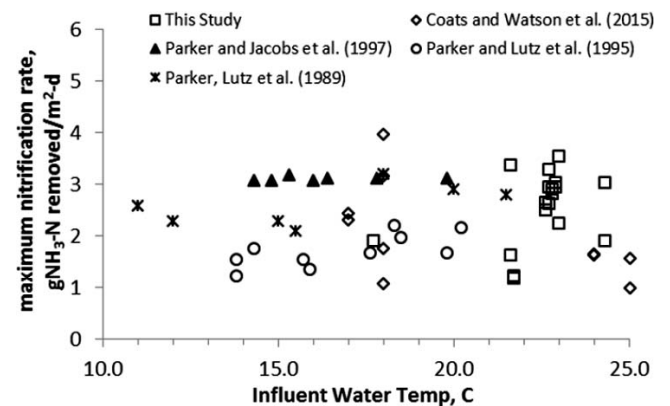


Figure 5—Calculated maximum zero-order/maximum nitrification rates (Table 2) plotted against influent water temperature.

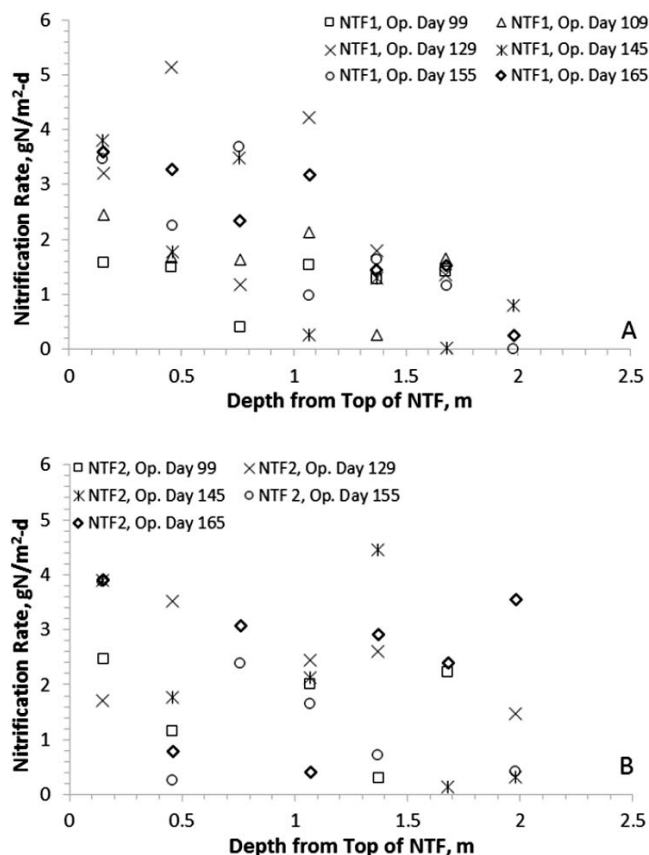


Figure 6—Calculated nitrification rate vs. depth for NTF1 (A) and NTF2 (B).

NTF as $r_{n,max}$. However, as shown by some of the same investigators (Lutz et al., 1995; Parker et al., 1995), and for one data set in this study (Table 2), the nitrification rate measured at the top layer of the NTF is not always the $r_{n(max)}$; even more critically, $r_{n(max)}$ can greatly exceed $r_{n(max,0)}$ (Table 2). Awareness of this distinction, and understanding the cause, is important when selecting the design maximum nitrification rate, as use of published $r_{n(max)}$ values could lead to NTF performance issues (relative to permit requirements). Additional commentary on the differences, and a likely explanation for the differences, follows.

$r_{n(max)}$ values from this study (calculated consistent with prior studies) are presented together with the $r_{n(max,0)}$ values in Table 2. As shown, the $r_{n(max)}$ values as measured in the top layer of the pilot NTFs were consistently higher than $r_{n(max,0)}$ – sometimes substantially higher (e.g., day 168 for NTF1). In a second comparison, calculated nitrification rates within the pilot NTFs and at different depths are illustrated in Figure 6. As shown for NTF1 (Figure 6A), r_n remained relatively high in approximately the upper half of NTF1, then decreased substantially in the lower half of the NTF. Performance in NTF2 (Figure 6B) differed from that of NTF1, in that the nitrification rates remained relatively high throughout. As noted (see also Table 1), NTF2 was operated at a higher ammonia-N loading rate than NTF1, and as observed by Parker et al. (1989), r_n can remain relatively constant throughout an NTF if the influent ammonia-N load is sufficiently large. The explanation

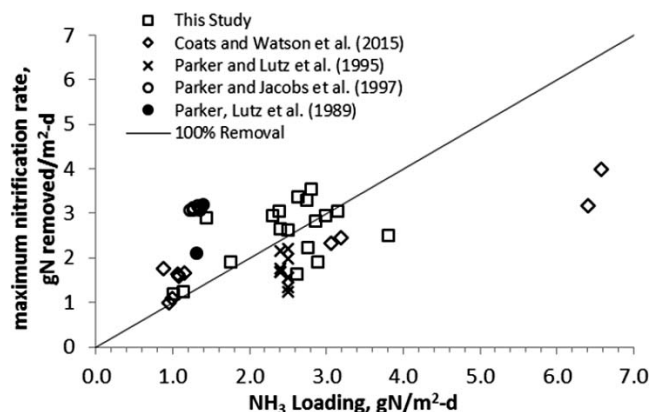


Figure 7—Graphical analysis and comparison of NTF loading (gN/m²-d; based on actual NTF media surface area) vs. maximum zero-order/maximum nitrification rate.

for the differences in maximum nitrification rate presented herein and elsewhere relates to the resolution, or depth interval, of ammonia-N measurements. This study measured ammonia-N at closely spaced intervals in the NTF (30 cm intervals), while, for example, Parker et al. (1989, 1995) measured ammonia-N at much larger intervals (120 cm). Certainly this resolution of measurements can affect r_n ; closer spaced measurements would likely yield larger $r_{n(max)}$ values (similar to measuring reaction rates on shorter time intervals in a suspended growth reactor).

Clearly, considering the above discussion, selecting a design r_n value based on the peer-reviewed literature is not clear-cut. Care must be taken to ensure that the design $r_{n(max)}$ value is not too large; selecting $r_{n(max,0)}$ as presented herein would appear to be a more conservative approach, and more broadly reflective of performance to deeper regions of the NTF. In this regard, the presented relationships between the design influent ammonia-N concentration or load and $r_{n(max,0)}$ (including the $r_{n(max)}$ values obtained by others, as cited herein; Figure 4) are useful to engineers. Further, $r_{n(max,0)}$ (and $r_{n,max}$ by others) was evaluated against the design ammonia-N loading (Figure 7). Up to an ammonia-N loading rate of approximately $3 \text{ gN m}^{-2} \text{ d}^{-1}$, within the zero-order region there exists a relationship wherein most of the applied ammonia-N should be oxidized. These latter results are similar to those observed and presented by Okey and Albertson (1989).

Transition from Maximum Zero-Order Nitrification. At high ammonia-N concentrations the NTF nitrification rate, r_n , is impacted by limited oxygen diffusion into the biofilm (Gullicks and Cleasby, 1986; Okey and Albertson, 1989; Parker et al., 1975), and maximum zero order ammonia-N removal kinetics prevail. As the ammonia-N concentration decreases, ammonia-N diffusion into the biofilm begins to affect nitrification, and the nitrification rate can decrease to some value less than maximum. Parker et al. (1995) appeared to observe the transition from zero to first order nitrification at approximately 5 mgN/L, while Albertson and Okey (1989) suggest a transition at 3–4 mgN/L. In this study the transition concentration from $r_{n(max,0)}$ ranged from 0.9–22.2 mgN/L (Table 2), and appeared significantly affected by the ammonia-N loading (Figure 8).

Decreasing NTF Nitrification Rate with NTF Depth. As described, Gujer and Boller (1986) proposed a “line fit”

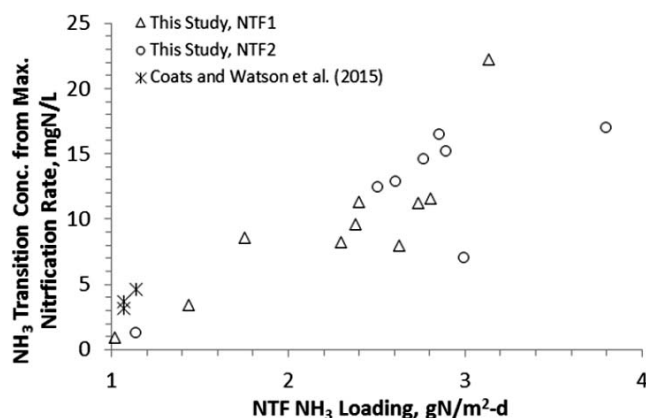


Figure 8—Estimated transition ammonia concentration from maximum zero-order nitrification vs. NTF depth.

relationship to model the potential decrease in nitrification rate within an NTF, with the relationship being exponential as shown in eq 1. Conversely, the approach suggested by Okey and Albertson (WEF, 2010) would employ a linear, more simplified mix of zero- and first-order kinetics. For the design engineer, if the Gujer and Boller design method is employed, a value is needed for the “ k ” parameter that models the exponential decrease in nitrification. Some limited empirical data can be found in the peer-reviewed literature (Coats et al., 2015; Parker et al., 1989, 1997), with values ranging from 0.075–0.257; WEF MOP#8 (WEF, 2010) recommends a value of 0.1, with a range of 0–0.16. Ultimately, however, the design engineer has very limited guidance in selecting this value. Similar challenges exist in employing the Okey and Albertson method.

In this study, as shown in Figure 6A, the nitrification rate ultimately decreased within the NTF for many events characterized for NTF1, while NTF2 realized a more muted decrease in nitrification (largely attributed to a higher ammonia-N loading rate, as noted). However, in contrast to the model proposed by Gujer and Boller, the relationship for the decrease in nitrification was not exponential. The Gujer-Boller exponential equation was

fit to the data, but the correlation in all data sets was poor. Rather, for NTF1, the nitrification rate at depths below the $r_{n(\max,0)}$ region remained zero-order, but at a smaller rate than $r_{n(\max,0)}$ (for example, see Figures 3B and 3D). The smaller zero-order nitrification rates, $r_{n(0)}$, along with the associated ammonia-N concentrations, are presented in Table 3; data from Coats et al. (2015) is included in Table 3. Analysis of data from Coats et al. (2015) revealed a limited fit to the Gujer-Boller exponential equation, with the lower zero-order nitrification rate predominating.

Media Effectiveness Factor. Parker et al. (1989) proposed a Media Effective Factor, E (in eq 2), to relate $r_{n(\max)}$ with the NTF media oxygen transfer rate. The E value accounts for operational variability within an NTF that can decrease $r_{n(\max)}$ relative to the theoretical maximum value (based on $r_{(O_2, \max)}$), principally associated with lack of complete media wetting, biofilm predators, and/or electron acceptor competition between autotrophic and heterotrophic organisms (Parker et al., 1989). More generally, E reflects a patchy biofilm developed on the NTF media (Gujer and Boller, 1986). The purpose of the E value is to allow the engineer to utilize, and adjust, empirical $r_{n(\max)}$ values developed for a given media more universally to other media and other NTF systems.

The E value was calculated for all $r_{n(\max,0)}$, $r_{n(0)}$, and $r_{n(\max)}$ values determined in this study (Tables 2 and 3), with the value of $r_{(O_2, \max)}$ estimated using the Logan trickling filter model (Logan, 1993, 1995; Logan et al., 1987) for the cross-flow media used. The calculated E values were generally consistent with that measured by others (Coats et al., 2015; Parker et al., 1989, 1995, 1997). For the E values exceeding unity, it would appear that the NTFs were operated near or at maximum capacity (comparing actual ammonia-N loading ($\text{gN m}^{-2}\text{d}^{-1}$) vs. $r_{n(\max,0)}$, and where $r_{n(\max,0)}$ is greater than the ammonia-N loading). As a point of clarification, the cross flow media used in this and our previous study was rated at a surface area:volume ratio of $157 \text{ m}^2/\text{m}^3$; the data from Parker and coworkers was also cross flow media, but with $138 \text{ m}^2/\text{m}^3$. The E values were plotted against the nitrification rates ($r_{n(\max,0)}$ and $r_{n(0)}$ for this study, or $r_{n(\max)}$ as reported by Parker and coworkers); this chart, coupled with

Table 3—Summary zero-order nitrification rate data.

Operational day	NTF	Water temp., °C	$r_{n(0)}^1$, $\text{gN m}^{-2}\text{d}^{-1}$	Empirical E^2	NH_3 at transition from $r_{n(\max,0)}$, mgN/L	Effluent NH_3 , mgN/L
109	1	17.7	0.55	0.19	8.6	6.8
119	1	21.6	1.58	0.54	8.0	4.6
145	1	22.8	0.62	0.21	3.4	<0.1
155	1	24.3	1.02	0.35	22.2	16.9
165	1	22.9	1.12	0.38	9.6	5.0
168	1	23	1.38	0.47	11.6	5.3
169	1	22.7	0.71	0.24	8.2	5.5
172	1	22.7	1.15	0.39	11.2	6.5
174	1	22.6	1.00	0.34	11.3	6.7
Year 1 ³	1	25	0.76	0.26	2.3	0.2
		24	0.66	0.23	3.7	0.4
		24	0.71	0.24	3.2	1.2
Year 3 ³	1	18	0.24	0.08	1.2	0.2

¹ Zero-order ammonia removal rate constant (not $r_{n(\max,0)}$).

² Media Effectiveness Factor (Parker et al., 1989); based on data from this study (see eq 2) and calculated based on an $r_{(O_2, \max)}$ of $12.55 \text{ gO}_2/\text{m}^2\text{-d}$ (estimated using the Logan trickling filter model (Logan, 1993, 1995; Logan et al., 1987)).

³ Coats and Watson et al. (2015).

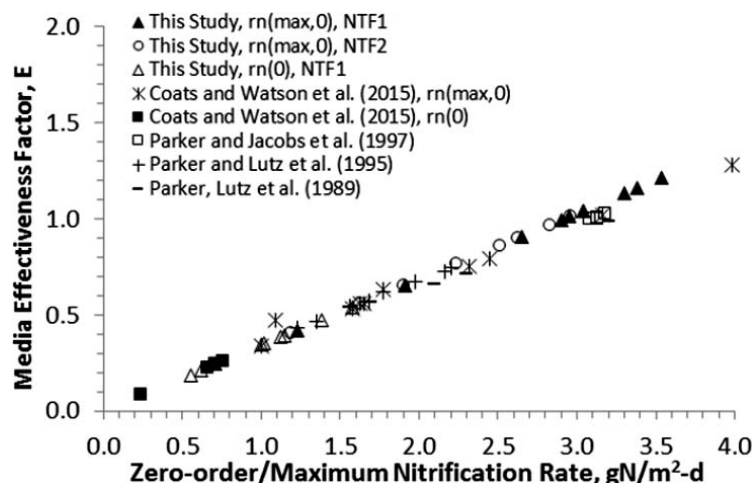


Figure 9—Calculated NTF media effectiveness, E, vs. zero-order/maximum nitrification rate.

other data presented herein, will greatly assist the engineer in selecting NTF design parameters, because this chart can be used to select a design maximum zero-order nitrification rate for a different media.

Conclusions

Research presented and discussed herein focused on the analysis of nitrifying trickling filter (NTF) pilot-scale data to develop enhanced data sets and refined guidance for the modeling/design of NTFs. In particular, there is inconsistency in the presentation and determination of design maximum nitrification rates in the peer-reviewed literature, which can lead to potential confusion in the design of NTFs. Key conclusions are as follows:

- In this study, the maximum zero-order nitrification rate, $r_{n(\max,0)}$, was calculated based on observed ammonia-N removal within a NTF. As a contrast, peer-reviewed literature presents $r_{n(\max)}$ as the maximum nitrification rate observed at the top of the NTF. The difference is critical in the modeling and design of NTFs, as described herein.
- Maximum zero-order nitrification rates ($r_{n(\max,0)}$), ranging from 1.19–3.38 $\text{gN m}^{-2}\text{d}^{-1}$, were found to be correlated with both influent ammonia-N concentration and loading. Conversely, $r_{n(\max)}$ values were consistently larger than $r_{n(\max,0)}$. Applying the latter in NTF modeling/design would likely lead to under-sizing the NTF.
- The transition concentration from $r_{n(\max,0)}$ to a reduced nitrification rate ranged from 0.9–22.2 mgN/L , and appeared significantly affected by ammonia-N loading.
- A second zero-order nitrification rate ranging from 0.24–1.58 $\text{gN m}^{-2}\text{d}^{-1}$ (less than $r_{n(\max,0)}$) was observed within a pilot-scale NTF. In contrast with previous NTF models, first-order nitrification was not observed, nor was there a strong exponential correlation for decreasing nitrification rate with the NTF.
- A chart has been developed for the relationship between the NTF media effectiveness parameter, E, and the design maximum nitrification rate to assist engineers in establish-

ing design nitrification rates for NTF media different from that utilized herein.

Collectively, the analyses and data presented herein should greatly enhance the engineer's ability to design full-scale NTFs.

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