

Performance of a Pilot-Scale Nitrifying Trickling Filter Treating Municipal Aerated Lagoon Effluent

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ABSTRACT: Colfax, WA, operates an aerated lagoon to achieve compliance with its National Pollutant Discharge Elimination System (NPDES) permit, which currently requires biochemical oxygen demand (BOD) and total suspended solids (TSS) removal. However, ammonia removal may soon be required, and Colfax is considering a nitrifying trickling filter (NTF) that would allow them to also maintain the lagoons. To obtain data from which to ultimately design a full-scale system, a four-year NTF pilot study was performed. Results demonstrated that an NTF would be an effective, reliable NH_3 removal method and could produce effluent NH_3 concentrations < 1.0 mg/L. NTF performance was characterized by zero- and first-order kinetics; zero-order rates correlated with influent NH_3 concentrations and mass load. Utilizing data from these investigations it was determined that the pilot NTF could be reduced by 19%, which demonstrates the value of pilot testing. Finally, pilot data was evaluated to provide a data set that will be useful to engineers designing full-scale NTFs. *Water Environ. Res.*, **87**, 35 (2015).

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Introduction

Excess ammonia-nitrogen (NH_3) in reclaimed water discharged to surface water bodies is toxic to certain aquatic organisms and can also contribute to accelerated water body eutrophication. As a consequence, water resource recovery facilities (WRRFs) are increasingly facing new effluent NH_3 discharge limits. These new permit requirements are particularly challenging to smaller municipalities that have historically favored low cost, simple facultative or aerated lagoon treatment systems focused on the removal of biochemical oxygen demand (BOD). Lagoon systems are prevalent across the U.S.; in the Pacific NW region of the U.S. alone there are 63 permitted lagoons operating in Washington, 59 in Oregon, and 40 in Idaho (data obtained from public databases for NPDES-permitted WRRFs). Many of these facilities could soon realize NH_3 removal requirements; facultative and aerated lagoons cannot consistently remove NH_3 , which will thus require significant and costly WRRF upgrades and expansions.

The most traditional approach to NH_3 removal from wastewater has been to employ the activated sludge process,

which is highly efficient at ammonia removal. Activated sludge treatment requires one or more aeration basins in series coupled with primary and secondary clarifiers, mechanical aeration systems, and associated recycling/wasting pumps. Moreover, activated sludge treatment produces excess quantities of sludge that requires treatment/management. While activated sludge treatment is very efficient and broadly popular for achieving wastewater NH_3 removal, it is not always a practical technology option for smaller communities with limited budgets and resources. As contrasted with lagoon systems, activated sludge facilities require more specialized operators (and often more operators) and are significantly more expensive to operate and maintain.

In considering alternative treatment configurations for NH_3 removal, trickling filters (TFs) represent a simpler operation and a potentially less costly technology. TFs, which have been utilized to achieve wastewater treatment for over a century, are non-submerged fixed film biological reactors filled with rock or plastic media over which wastewater is distributed semi-continuously (Tchobanoglous et al., 2014). Historically TFs were used principally for the removal of BOD from wastewater. However, TFs can also be used to target NH_3 removal, specifically treating secondary effluent low in BOD and suspended solids; TFs used in this application are referred to as nitrifying trickling filters (NTFs), with demonstrated use beginning in the early 1970s (Parker et al., 1990). Although not a new treatment approach, NTFs remain an underused technology at full scale.

The potential benefits to NTFs for NH_3 -focused wastewater treatment are many and have been described by others (e.g., Daigger and Boltz, 2011)). Excellent descriptions of biofilm kinetics and associated theoretical TF models have been developed and presented (e.g. Rittmann and McCarty, 2001); full-scale design guidance builds upon the fundamental mechanistic, but employs a more simplified kinetics approach that benefits from empirical data (Grady Jr. et al., 2011; Krause, 2010; Tchobanoglous et al., 2014). While quality empirical data sets from pilot and/or full scale operations are available (e.g. Andersson et al., 1994; Boller and Gujer, 1986; Goldstein and Smith, 2002; Gullicks and Cleasby, 1986; Mofokeng et al., 2009; Parker et al., 1995; Parker et al., 1989; Parker et al., 1997), of the extensive data sets that were reviewed, only those published by Parker and coworkers include detailed kinetic data within the NTF. The value and importance of such kinetic 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 NTF design models all integrate and require zero- and first-order NH_3 removal kinetic parameters.

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The city of Colfax, WA, located in southeastern Washington State, operates an aerated lagoon WRRF to produce reclaimed water in compliance with its state-issued 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 NH_3 limits to Colfax's permit (based on a review of other regional WRRFs, Colfax might realize a permit limit in the range of 1 to 4 mg NH_3/L). 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. However, there are no NTFs currently operating in Washington or elsewhere in the region from which to derive valuable performance data to facilitate a potential full-scale NTF design. The city thus commissioned an extended pilot-scale NTF study at their WRRF site, with the purpose to collect data and establish results that would 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. Specific objectives of this study were to i) establish NTF treatment potential on Colfax's aerated lagoon effluent, ii) assess NTF capacity over a range of hydraulic and NH_3 loading conditions, iii) obtain site- and wastewater-specific NTF kinetic data within the depths of the operating system, and iv) refine the design approach applied in sizing the pilot-scale NTF, based on the study's data, as related to a future full-size NTF. Not only did the study provide the city with important design and operational data, considering the dearth of NTFs in the region, the Washington State Department of Ecology (DOE; which issues NPDES permits in the state) favorably viewed the project for a potential future full-scale NTF project. This manuscript presents and discusses results from the pilot NTF study.

Materials and Methods

Description of the Colfax, WA WRRF. Colfax owns and operates a wastewater system to receive and treat wastewater derived from residential, commercial, and industrial services located within the city limit. Two aeration lagoons operated in series form the central biological treatment system, targeting the removal of BOD. Aeration Lagoon 1 has a volume of approximately 15,140 m^3 (4.0 million gallons) and a surface area of approximately 0.4 ha (one acre); it contains 41 submerged tube aerators. Aeration Lagoon 2 has a volume of approximately 17,000 m^3 (4.5 million gallons) and a surface area of approximately 0.61 ha (1.5 acres); it contains 14 submerged tube aerators. Air is supplied to both lagoons by three variable-speed positive displacement blowers providing 8.5 to 15.6 m^3 (300 to 550 ft^3) of air per minute each. At the outlet from Aeration Lagoon 2 is a 60-degree settling tube module that removes algae before chlorine disinfection.

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 NH_3 basis, the pilot system was designed to treat an influent maximum concentration of 25 mg $\text{NH}_3\text{-N}/\text{L}$, with a target effluent concentration of 1 mg $\text{NH}_3\text{-N}/\text{L}$. Analysis of lagoon effluent indicated that the NTF influent total BOD would be less than 10 mg/L; at this low concentration, the effect on NTF performance associated with competitive growth of heterotrophic microorganisms was expected to be minimal (Parker and Richards, 1986). The NTF was designed in

accordance with procedures described by Tchobanoglous et al. (2014). Specific design assumptions were as follows: maximum rate of NH_3 removal ($r_{n, \text{max}}$) of 1.5 $\text{gN}/\text{m}^2\cdot\text{d}$; nitrification half saturation coefficient (K_n) of 1.5 mg/L; coefficient ' γ ' (characterizing the decrease in nitrification rate with depth) of 0.2; and the transitional NH_3 concentration from zero- to first-order nitrification of 4.5 mg N/L.

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 NH_3 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 (16 ft). Two NTFs in series, each 2.44m (8 ft) 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 is 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 NTF1 using a 0.373 kW (0.5 hp) sump pump (Liberty Pumps, Bergen, NY, USA); the same make/model pump is used to transfer NTF1 effluent to NTF2. The pilot NTF utilizes a tipping bucket to distribute influent over the media, with 50% of the NTF surface area dosed for each "tip." This dosing mechanism pulsed a relatively large volume 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 evaluated in this study ranged from 6 to 38 mm/tip, 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 m^3/min [5.6 ft^3/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 (the lagoon effluent, which was aerated, exhibited a dissolved oxygen concentration exceeding 1 mg/L). To facilitate kinetic analysis of the NTFs, three 5 cm (2 in) diameter holes were drilled across one side of each NTF tower at heights of 40, 96, 162.5, and 208 cm (16, 38, 64, and 82 in) above the bottom of the media.

NTF Operation. The NTF system was operated during the late winter/early spring into summer months over a period of four years (Table 1). In year 1 the NTF system was operated at its design hydraulic loading rate. Year 2 operations assessed system capacity, with the hydraulic loading rate increased by a factor of 2.7. In years 3 and 4 the hydraulic loading rate was reduced to approximately the original design condition. The operational period was based on i) anticipated DOE NPDES criteria only requiring ammonia removal during low stream flow summer

Table 1—Summary of NTF operational criteria.

Year and operational period (month/day)	Flow rate m ³ h ⁻¹ (gal min ⁻¹)	HLR ¹ m h ⁻¹ (gal d ⁻¹ (ft ²) ⁻¹)	sHLR ² m h ⁻¹ (gal d ⁻¹ (ft ²) ⁻¹)	Avg. NH ₃ loading rate g N m ⁻² ·d (±std. dev.) (max/min)		NH ₃ addition started
				NTF1	NTF2	
1: 6/1–8/3	2.84 (12.5)	1.91 (1,125)	0.0025 (1.46)	1.3±0.8 (3.2/0.6)	0.8±1.2 (3.3/0)	None
2: 5/18–9/29	7.74 (34.1)	5.20 (3,069)	0.0068 (4.0)	6.8±2.3 (12.6/1.1)	3.3±2.6 (9.9/0.1)	Day 53
3: 2/29–4/4	3.11 (13.7)	2.09 (1,233)	0.0027 (1.61)	1.6±0.4 (2.9/0.7)	0.6±0.4 (2.7/0)	None
4: 2/26–6/6	3.31 (14.6)	2.22 (1,314)	0.0029 (1.71)	3.1±0.5 (4/2)	2.1±0.7 (3.3/0.5)	None

¹ calculated as Flow Rate divided by NTF plan view surface area.

² calculated as Flow Rate divided by actual NTF media surface area (both NTFs).

months, and ii) eventual lagoon nitrification in mid/late summer that resulted in no ammonia available for the NTFs (see Results and Discussion for more detail). Water samples were regularly collected at three locations: influent to NTF1, effluent of NTF1, and effluent of NTF2. Additional samples were collected intermittently within the NTF for a more detailed kinetics analysis. Each of the samples were filtered on site and later tested for NH₃. Dissolved oxygen and pH were measured at the lagoon settling tube and the pump basin between NTF1 and NTF2.

Analytical Techniques. For all soluble constituents, samples were filtered through a 0.22 µm syringe filter (Millipore Corp., Billerica, MA, USA) prior to testing. NH₃ testing followed 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 NH₃. NH₃ concentrations were determined utilizing a standard curve ($R^2 > 0.99$). DO measurements were collected using a Hach HQ30d Meter with a LDO101 probe. pH was measured using a Fisher Scientific AP 72 meter and pH probe.

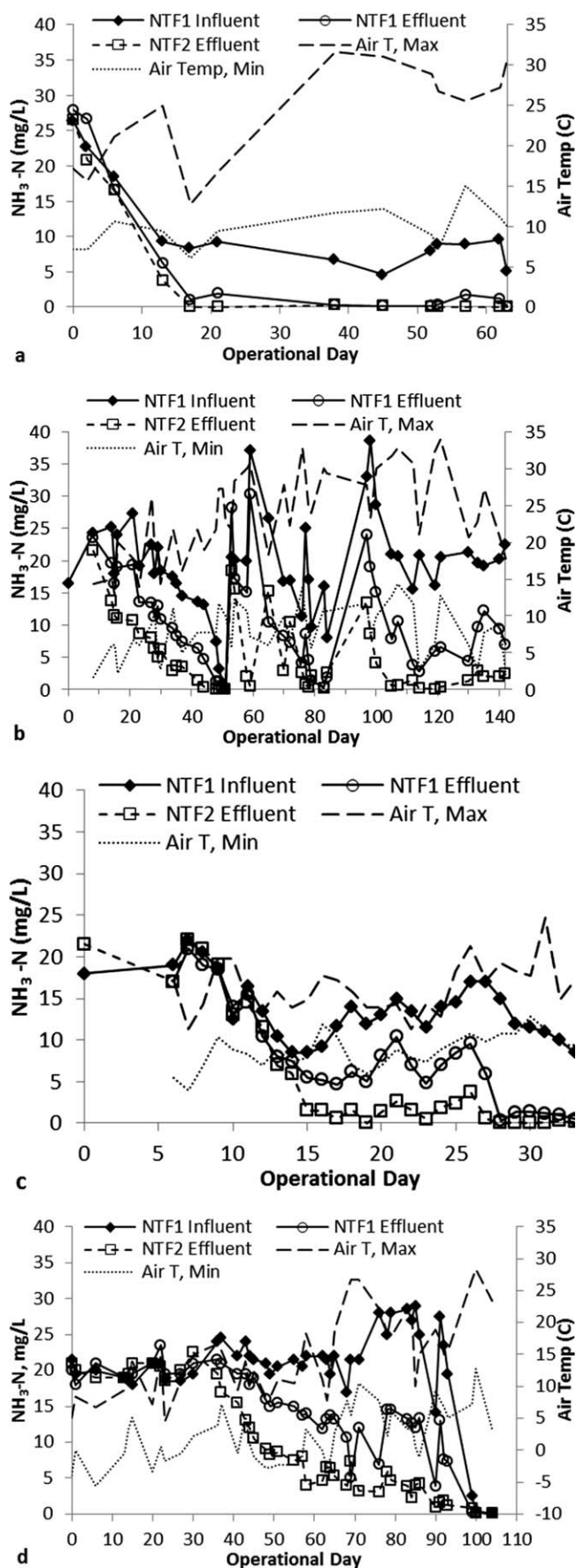
Results and Discussion

NTF Performance. In year 1 the pilot NTF was operated for 63 days (Table 1); operations were ultimately cut short due to lagoon nitrification and associated loss of substrate. As shown in Figure 1a, development of an autotrophic biofilm and associated nitrification in NTF1 and NTF2 was achieved by day 12. With ambient air temperature relatively warm (Figure 1a; ranging from 10 to 24 °C), rapid biofilm development was expected. Once the biofilm was established, effluent NH₃ rapidly decreased below 1.0 mg/L. The lagoon was increasingly nitrifying during the 12 day NTF acclimation period; thereafter the NTF influent concentrations averaged 7.9±1.8 mg NH₃/L. At the applied hydraulic and NH₃ loading, ultimately only NTF1 was necessary to treat the lagoon effluent (Figure 1a). Although the pilot system was initially loaded near its design condition, once lagoon 2 started nitrifying the applied loading was significantly less than design. The DO consistently exceeded 3.0 mg/L in the lagoon 2 effluent, increasing to more than 5.0 mg/L in the NTF2 effluent.

Year 2 pilot operations were commenced approximately one month earlier than year 1 (Table 1) to obtain more operational data before the lagoons nitrified. As described, the hydraulic loading rate was also increased to better evaluate system treatment capacity; note the commensurate increase in NH₃ loading (Table 1). A functioning biofilm in the NTFs appeared to

have sufficiently developed between day 10 and 20, and an effluent concentration below 5 mg NH₃/L was achieved by day 30. However, despite attempts to gain additional NTF operational data before lagoon nitrification, as shown in Figure 1b, lagoon nitrification occurred earlier than the year prior; after 51 days of operation the lagoons had achieved complete nitrification. Considering the need to obtain more NTF operational data, it was decided to augment the NTF influent with anhydrous ammonia; operations commenced on day 53, increasing the influent NH₃ to concentrations necessary to support NTF biological functions. With the inherent volatility of anhydrous ammonia and reduced stock concentration over time associated with off-gassing, the resulting influent NTF NH₃ concentration varied over the remainder of the operational period (8–36.8 mg NH₃/L; average of 20.8±7.2 mg NH₃/L). Effluent from NTF1 and NTF2 responded similarly to the varied NH₃ load, yet on average the NTF1 and NTF2 effluent averaged 10.2 (±7.8) and 4.2 (±5.5) mg NH₃/L, respectively (overall 80% NH₃ removal). For days 105 to 142 the influent, and NTF1 and NTF2 effluent, averaged 19.8 (±2.1), 7.3 (±3.0) and 1.3 (±1.0) mg NH₃/L, respectively (overall 93.5% NH₃ removal). As a contrast to year 1, due to the increased loading rate ultimately both NTFs were required to treat the influent wastewater. Although the NTF system was loaded both hydraulically and inorganically (in year 2) well in excess of the original design criteria, the observed treatment performance was excellent, indicating that the design method was conservative.

With a quality operational data set collected in years 1 and 2, attention turned to evaluating NTF startup further. Specifically, should Colfax be required to nitrify, the NPDES permit period would potentially commence between April 1 and May 1; testing in years 1 and 2 started well after a permit period would commence. Thus, in year 3 the NTF pilot was started on February 29, while in year 4 operations commenced February 26. As shown for year 3 (Figure 1c), the NTF system started realizing treatment after 14 operational days; thereafter, effluent NH₃ remained less than 2 mg NH₃/L. Between days 14 and 35 the influent NH₃ concentration was 11.9±3.2 mg NH₃/L, while NTF1 and NTF2 effluent averaged 4.4±3.3 and 1.0±1.0 mg NH₃/L (overall 92% NH₃ removal). The ambient air temperature ranged from 0.6 to 9.1 °C, much colder than observed in years 1 and 2. Similar to observations in year 2, both NTFs were required to achieve the treatment goal. In contrast to year 3 performance observations, year 4 NTF operations did not realize measurable treatment until approximately day 45 (April 12; Figure 1d), and not until day 90 (May 27) did the NTF2 effluent approach 1.0 mg NH₃/L. While in year 3 the lagoon NH₃



concentration decreased from approximately 20 to 8 mg NH₃/L before NTF treatment was observed, in year 4 the influent NH₃ concentration averaged approximately 20.8±2.0 mg NH₃/L before treatment was realized. Moreover, lagoon effluent averaged approximately 21.9±3.3 mg NH₃/L over the 93-day operational period before the lagoons nitrified (Figure 1d). As a consequence, NTF1 was loaded at approximately twice the rate in year 4 as compared to years 1 and 3 (NH₃-basis; Table 1), although essentially at the original design criteria. After operational day 45, effluent from NTF1 and NTF2 averaged 11.1±4.5 mg NH₃/L and 4.5±2.6 mg NH₃/L, respectively (overall 80% NH₃ removal); by day 91 (May 28), effluent from NTF2 was reduced below 2.0 mg NH₃/L. The ambient air temperature in year 4 during NTF acclimation was comparable to the year prior (0 to 10.4 °C), although it warmed after day 45 (3.2 to 17.6 °C). In considering year 4 data against year's 1 to 3, the late acclimation period and somewhat subdued overall performance may have been associated with the much higher ammonia loading rate coupled with prolonged and very cold conditions that prevailed; future scale-up will need to factor in the date of system start-up, coupled with temperature, in order to achieve necessary treatment.

Comparative NTF Performance Assessment. Overall, our pilot NTF system performed comparable to that observed in other pilot and full scale studies (Table 2). In contrast to the results of Parker et al. (1997), who studied a two-stage full scale NTF receiving a blend of secondary effluent and anaerobic digester centrate, our pilot NTFs produced similar quality effluent NH₃. While the media was effectively the same, the NTF configurations were markedly different; our NTFs were much taller with a smaller aerial footprint (area:height ratio of 0.6 in this study, compared to 110 in Parker et al. (1997)). As a consequence of the differing geometries, the gross hydraulic loading rate (HLR) was approximately 50% less in our study; however, the specific HLRs were comparable as were the NH₃ loading rates. Andersson et al. (1994) evaluated a pilot NTF (two units, each with an area:height of 1.58) over a two year period treating secondary effluent from an activated sludge WRRF; assessments were made both with a single NTF and with two operated in series. Comparatively, all tests were operated at a very low sHLR relative to the pilot-scale system evaluated herein, but their NH₃ loading rate was higher. When two NTF units were operated in series, performance was comparable to our study and that of Parker et al. (1997). However, when operated as single units and at half the NH₃ loading rate, the performance deteriorated. In a third comparative study, Mofokeng et al. (2009) investigated both a full-scale and lab-scale NTF (each a single reactor) treating effluent from a partially aerated lagoon. The NTFs had an area:height ratio of 5.6 and 0.014, respectively. The full-scale NTF did not exhibit good treatment performance (high effluent NH₃; overall NH₃ removal of 26 to 65%), likely due to very high concentrations of influent soluble COD (75 to 112 mg/L) coupled with higher sHLRs (generally >0.0031 m/h). Similarly, the pilot-scale system, which received a higher sHLR (0.0032 to 0.0053 m/h), exhibited less than 73% NH₃ removal along with elevated effluent NH₃ concentrations. It should be noted that the influent NH₃

Figure 1—Ammonia removal performance summary for NTF1 and NTF2 for (a) Year 1; (b) Year 2; (c) Year 3; and (d) Year 4.

Table 2—Comparative NTF performance with previous studies.

Reference	# of NTFs	Full or Pilot Scale	Operational Pattern	Media Density m^2/m^3	sHLR ¹ m h^{-1}	NH ₃ Loading Rate ¹ $\text{gN m}^{-2}\cdot\text{d}$	Effluent NH ₃ mg L^{-1}
(Parker et al., 1997)	2	Full	series	138	0.0022-0.0026	0.69-1.55	0.56-3.35
(Mofokeng et al., 2009)	1	Full	--	142	0.0016-0.0037	1.21-1.51	10.7-26.1
	1	Pilot	--	109	0.0032-0.0053	0.97-2.37	10.6-25.5
(Andersson et al., 1994)	2	Pilot	series	140	0.00057	5.0-5.1	0.4-2.4
	1	Pilot	--	140	0.00028	2.3-2.5	1.6-8.5
(Wall et al., 2002)	2	Full	parallel	150	0.0016-0.0034	0.4-0.5	0.4-1.1

¹based on the total media surface area of the NTFs (if operated in series, includes all NTFs).

concentrations to the NTFs studied by Mofokeng et al. were significantly higher (32–46 mg/L) than the other comparative studies discussed herein. As a final comparison, Wall et al. (2002) observed excellent NH₃ removal in a full scale NTF (single reactor). While the system was hydraulically loaded comparable to our study and the others cited herein, the NH₃ loading rate was markedly lower (Table 2), which likely led to the excellent treatment performance. In summary, considering our study and the comparatives discussed herein, it would appear that operating one NTF vs. two in series appeared to be an important factor in overall NTF performance and achieving low effluent ammonia concentrations. Gujer and Boller (1986) made such recommendations, and further suggested alternating ‘lead’ operations regularly to maintain a homogenous and productive biomass.

Nitrification Kinetics. Ammonia removal kinetics and associated NTF process design guidelines have been the subject of intense investigation and discussion over the years, beginning with a focus on “apparent” nitrification rates that only considered influent/effluent NH₃ (Gullicks and Cleasby, 1986; Okey and Albertson, 1989) and culminating in the consideration of differential NH₃ removal rates within and down through the NTF tower (Andersson et al., 1994; Gujer and Boller, 1986; Parker et al., 1995; Parker et al., 1989). An excellent review on the evolution of NTF nitrification kinetics theory is presented by Parker et al. (1989); what follows is an abbreviated review to provide necessary context for this work.

Early research on NTFs and nitrification kinetics concluded that at high NH₃ concentrations (suggested at >3–4 mg NH₃/L) the NTF nitrification rate, r_N , is impacted largely by limited oxygen diffusion into the biofilm (Gullicks and Cleasby, 1986; Okey and Albertson, 1989; Parker et al., 1975). Specifically, under high NH₃ concentrations it was concluded that zero order ammonia removal kinetics prevail, while first-order ammonia removal kinetics occur at lower NH₃ concentrations (<3–4 mg NH₃/L) and when NH₃ diffusion into the biofilm controls. As noted, these early r_N interpretations were based principally on considering only NTF influent/effluent NH₃ data. However, building from early investigations (based on a mix of pilot and full scale systems), the zero/first order debate was extended to examine in more detail the

nitrification rates within the NTF by collecting additional data. Research by Gujer and Boller (1986) and later by Parker et al. (1989) proposed that r_N should be calculated through assessing NH₃ removal in stages down an NTF, rather than adopting the more constrained and overly simplistic zero/first order approach. 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 NH₃ load remains relatively uniform throughout the NTF, the kinetics of NH₃ removal remain relatively constant throughout, however, ii) when the NH₃ 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). The observed decrease in nitrification rates with depth in the NTF has been associated with incomplete active biofilm development on the media due to variable NH₃ loading (Gujer and Boller, 1986). Parker et al. (1995) appeared to observe the transition from zero to first order nitrification at approximately 5 mg NH₃/L. As a practical note, the latter phenomena would be more likely encountered in full-scale NTFs.

Considering past NTF research and mechanistic biofilm theory (e.g., Rittmann and McCarty, 2001) within the context of recommended design practices for NTFs (Grady Jr et al., 2011; Krause, 2010; Tchobanoglous et al., 2014), it is clear that full-scale NTF design can benefit by determining actual NH₃ removal rates within the NTF. Thus, our study assessed nitrification kinetics within the respective NTFs for all four years of the investigation. For each NTF, water samples were collected at 12 different locations and at four levels (plus influent/effluent) within the NTF. Ammonia removal rates within the NTF were evaluated to determine if zero or first order kinetics prevailed; zero-order kinetic parameter estimation was performed consistent with Tchobanoglous et al. (2014) based on the concentration gradients observed within the NTFs (Figures 2a and 2b). Indeed, both zero and first order nitrification was observed within the NTFs (Figures 2a, 2b; Table 3). The phenomenon of differential nitrification rates is consistent with that of Boller and Gujer (1986) and also with Parker et al. (1989), as discussed above, and is hypothesized to reflect non-uniform NH₃ loading vertically

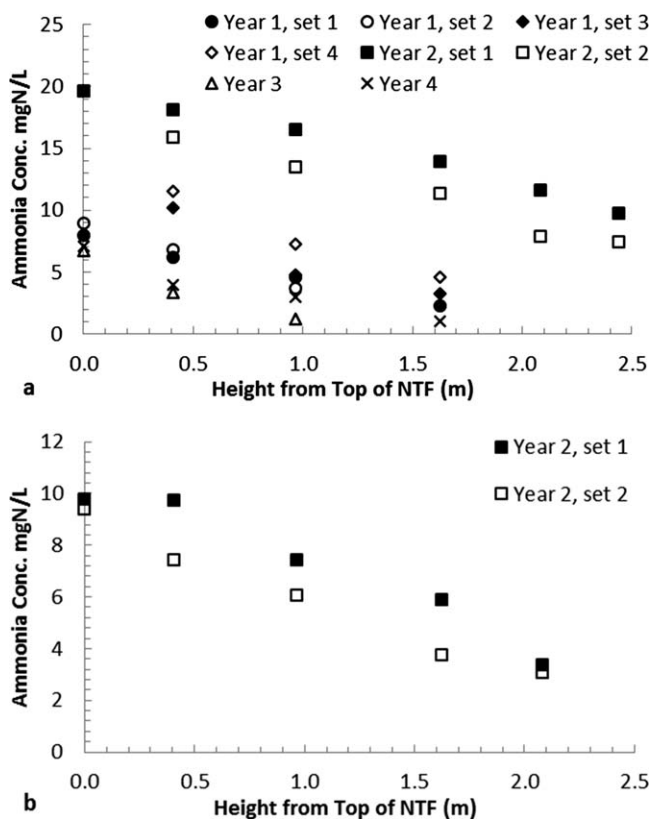


Figure 2—Ammonia-N concentration profiles within (a) NTF1 and (b) NTF2. Data was analyzed to determine zero-order kinetic parameters.

down through the NTF and associated non-uniform growth and distribution of the autotrophic biofilm.

Comparing $r_{N(0)}$ values with prior research, calculated coefficients were comparable to maximum r_N values determined by Parker et al. (1989), who observed rates ranging from 2.1 to 3.2 gN/m²•d using similar characteristic cross-flow media. Observed $r_{N(0)}$ values were also consistent with those reported by Parker (1999) for cross flow media. The variation in rates observed with influent NH₃ concentration was similar to that observed by Parker et al. (1995), although the lowest $r_{N(0)}$ values determined in this study (1.0–1.77 gN/m²•d) were slightly smaller than observed by others and presumably associated with relatively low influent NH₃ concentrations. Evaluating $r_{N(0)}$ vs. both influent NH₃ concentration and influent NH₃ loading (Figures 3a and 3b), a strong correlation existed with influent NH₃ loading, with influent NH₃ loading representing 89.6% of the variation observed in the zero-order nitrification rate. The relationship was statistically significant at a 1% Type I error rate ($p=0.00038$). Note also that the zero-order nitrification rate-influent ammonia concentration results (Figure 3a) aligned well with those obtained by others (Parker et al., 1989; Parker et al., 1997). Ammonia removal kinetics (zero order) did not appear to be significantly impacted by water temperature (Table 3); rather, ammonia mass loading appeared to be more important. Similar observations were made by Parker et al. (1989) for a comparable pilot-scale NTF study. Finally, the observed transition NH₃ concentration between zero and first order kinetics was generally consistent with that suggested by previous investigators (Gullicks and Cleasby, 1986; Okey and Albertson, 1989).

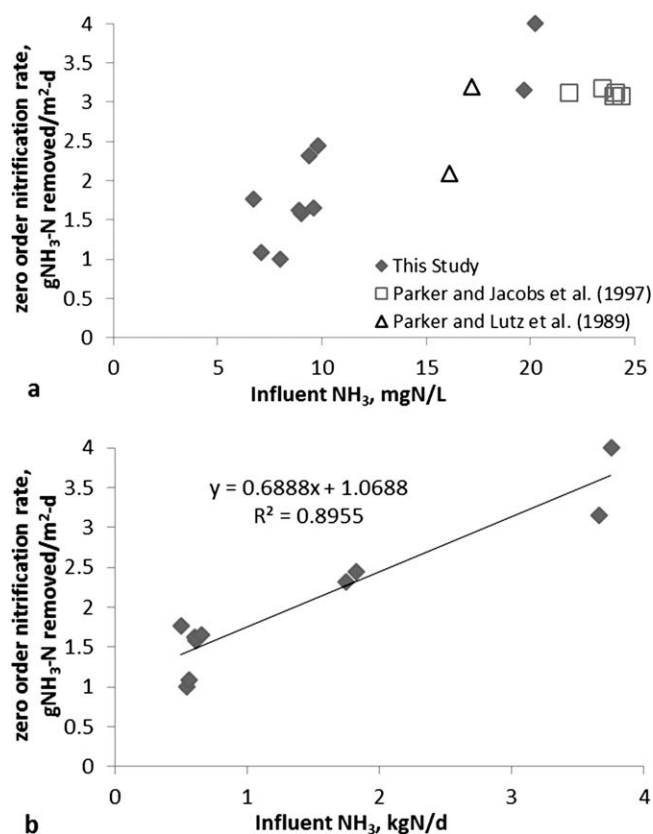


Figure 3—Graphical analysis and comparison of calculated NTF zero-order nitrification rates against (a) NTF influent ammonia (mg N/L) and (b) NTF ammonia-N loading (kg N/d).

Modeling Assessment for Future NTF Scale-up. Various theoretical and/or empirical models and approaches have been proposed for NTF design (e.g., EPA, 1975; Gujer and Boller, 1986; Gullicks and Cleasby, 1986; Okey and Albertson, 1989; Parker et al., 1989; Parker et al., 1975; Rittmann and McCarty, 2001), some more sophisticated than others. For example, 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. These more sophisticated mechanistic approaches have greatly informed biofilm modeling and NTF design, although to employ such approaches for full-scale design requires more knowledge on process kinetics and stoichiometry than is commonly available. As noted, an empirical-based approach was selected in the original design of the pilot-scale NTF system (Tchobanoglous et al., 2014). Indeed, consensus in the prominent design manuals (Grady Jr, et al., 2011; Krause, 2010; Tchobanoglous et al., 2014) has adopted the more simplified, empirical-based design approach centered on separately accounting for zero- and first-order ammonia-N removal. In this regard, 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 empirical-based NTF design. The equation includes empirical parameters to account for media effectiveness and to establish reduced nitrification rate with NTF depth (i.e., zero order and first order ammonia removal). In

Table 3—Summary kinetic and model analysis results for NTF performance.

Year	Influent NH ₃ , mg N L ⁻¹	Influent NH ₃ , kg N d ⁻¹	Effluent NH ₃ , mg N L ⁻¹	Water temp., °C	$r_{n(0)}^1$ g N m ⁻² •d ⁻¹	Empirical E^2	Theoretical E^3	Transition depth ⁴ , m	NH ₃ at transition ⁵ , mg N L ⁻¹	K^6 , m ⁻¹
1										
NTF1	8.0	0.55	0.2	25	1.00	0.34	0.82	1.6	2.3	0.67
NTF1	9.0	0.61	0.4	25	1.58	0.53	0.82	1.0	3.7	0.45
NTF1	8.9	0.61	1.2	24	1.63	0.56	0.79	1.6	3.2	0.38
NTF1	9.6	0.65	1.2	24	1.65	0.56	0.79	1.6	4.6	0.32
2										
NTF1	19.7	3.66	9.8	18	3.16	1.02	0.94	–	–	–
NTF2	9.8	1.82	2.9	18	2.45	0.79	0.94	–	–	–
NTF1	20.2	3.75	9.4	17	3.98	1.28	0.92	–	–	–
NTF2	9.4	1.75	2.0	17	2.32	0.75	0.92	–	–	–
3										
NTF1	6.7	0.50	0.2	18	1.77	0.63	0.68	1.0	1.2	0.41
4										
NTF1	7.1	0.56	1.2	18	1.09	0.47	0.69	1.3	2.0	0.20

¹ Zero-order ammonia removal rate constant.² Media Effectiveness Factor (Parker, Lutz *et al.*, 1989); based on this study - see equation (2).³ Calculated according to Parker and Lutz *et al.* (1995), excluding influent TSS.⁴ Measured from the top of the NTF.⁵ Transition from zero- to first-order nitrification.⁶ See equation (1).

addition to equation (1), Parker *et al.* (1989) proposed a relationship (equation (2)) to relate the maximum rate of ammonia removal (i.e., zero-order nitrification) with the media characteristics and associated surface oxygen transfer rate.

$$r_N = r_{N, \max} \left(\frac{N}{K_N + N} \right)^a e^{-kz} \quad (1)$$

$$tr_{N, \max} = \frac{E \cdot r_{O_2, \max}}{4.3} \quad (2)$$

Parameters for equations (1) and (2) are defined as follows.

r_N = nitrification rate at ammonia concentration N , g N/m²•d

$r_{N, \max}$ = maximum nitrification rate at ammonia concentration N , g N/m²•d

$r_{O_2, \max}$ = maximum surface oxygen transfer rate for the NTF media, g N/m²•d

N = bulk ammonia-nitrogen concentration in the NTF, mg/L

K_N = pseudo half saturation coefficient, mg/L (suggested to range from 1.0–2.0 (Grady Jr., *et al.*, 2011; Krause, 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 first-order 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 $r_{O_2, \max}$ varies with hydraulic loading, wastewater temperature, media characteristics, and can be calculated using the Logan trickling filter model (Logan, 1993, 1995; Logan *et al.*, 1987).

As noted, WRRF design manuals integrate equation (1) into NTF design guidance, with some simplifications. Both Grady Jr.

et al. (2011) and Tchobanoglous *et al.* (2014) recommend first accounting for zero-order removal based on a constant $r_{N, \max}$, consistent with the approach recommended by Albertson and Okey (1989); subsequent first order ammonia-N removal excludes the logarithmic-based portion of equation (1) and sets $a=1.0$. The WEF design manual (MOP#8; (Krause, 2010)) presents and discusses the models cited above, and also that of Albertson and Okey (1989) based on determinations of Wall *et al.* (2002) that showed the latter model better fitting real data; ultimately, MOP#8 makes no formal recommendations on model selection. While there is certain variation in design guidance (particularly in accounting for zero-order removal), ultimately all of the design guidance notes that the empirical values in equations (1) and (2) will be site specific and should be obtained with pilot-scale operations.

Recognizing that a primary goal of this NTF pilot project was to generate data necessary for potential future full-scale system design, data from the pilot NTF investigations were evaluated against equations (1) and (2) to extrapolate useful empirical parameters (specifically E and k). E values were estimated for the zero-order kinetic data collected (Table 3); media characteristics for the Logan trickling filter model were obtained with the aid of the manufacturer (Brentwood Industries, Reading, PA, USA) to calculate $r_{O_2, \max}$. As shown, E ranged from 0.34–1.28 and appeared strongly influenced by the influent ammonia load. The value of E has been estimated by others to range from 0.64 to 1.03 (Logan, 1995; Parker *et al.*, 1989; Parker *et al.*, 1997), with E_{avg} estimates for entire NTFs as low as 0.48 (Parker *et al.*, 1995). E values less than 1.0 represent inefficiencies in ammonia loading (which affects biofilm thickness), media wetting, predation of the biofilm, and/or competition for oxygen by heterotrophic microorganisms (Parker *et al.*, 1989); the type of media (e.g., cross flow vs. vertical flow) does not appear to influence the value of E (Logan, 1995; Parker *et al.*, 1989). Only for year 2 operations, where E ranged from 0.75 to 1.28, can it be interpreted that nitrification was occurring nearly at its

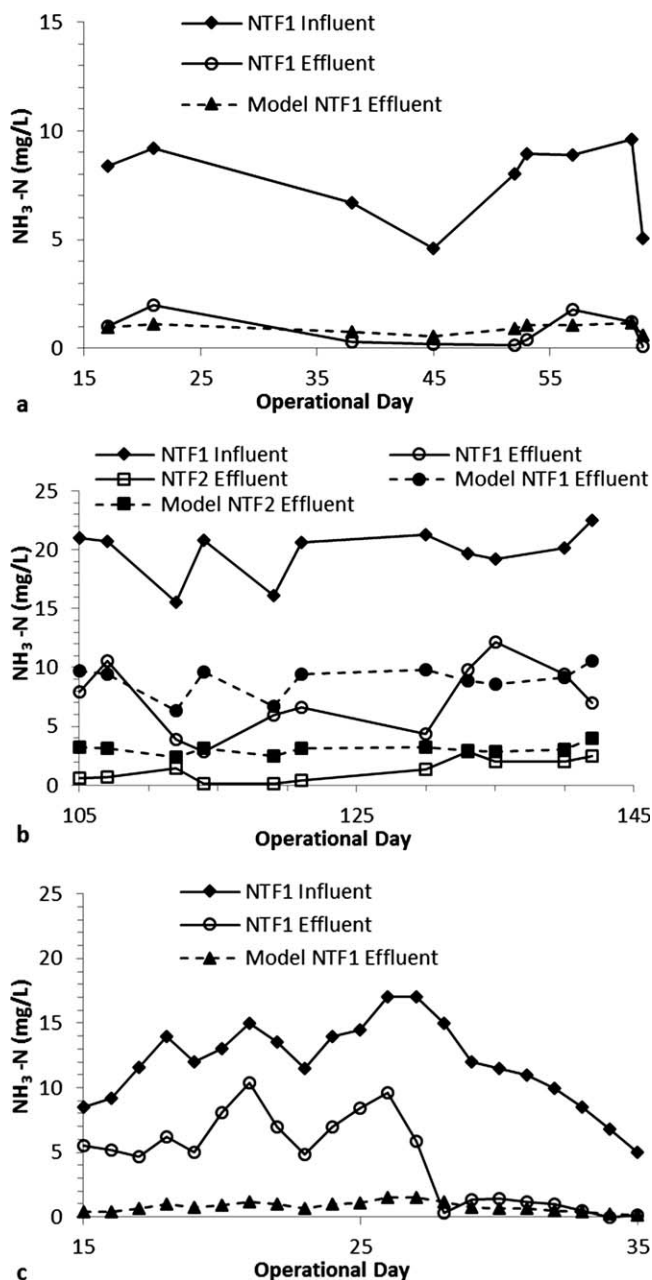


Figure 4—Actual vs. modeled effluent ammonia-N for (a) year 1, (b) year 2, and (c) year 3.

maximum rate (Parker et al., 1989); indeed, observed zero-order nitrification rates were highest in year 2, and also highest when $E > 1.0$. Finally, Parker et al. (1995) developed an equation for E based on temperature, influent TSS, and HLR; while they observed fit for their NTF study, no such fit was observed for this study (Table 3).

Regarding the coefficient k in equation (1), which pertains to first-order nitrification, the pilot NH_3 concentration data were evaluated within the zone determined to be exhibiting first-order ammonia removal, with the coefficient determined accordingly (Tchobanoglous et al., 2014). As shown, the k value ranged from 0.20–0.67. Gujer and Boller (1986) suggested that k is greater than zero under first-order ammonia removal and $k=0$ under

zero-order removal; as detailed, the approach taken herein separately evaluated first-order kinetics to determine k (hence, $k > 0$). Other investigators have estimated k to range from 0.0 to 0.257 (Krause, 2010; Parker et al., 1989; Parker et al., 1997) and have further suggested that k may be related to the value of E , with values of k decreasing as E increases (although a limited data set exists in this regard). However, no such correlation was observed with the data in this study.

Ultimately the value of conducting the pilot scale investigations lies in the ability to model and design a more efficient, cost-effective, and appropriate sized full-scale NTF system; two approaches were assessed in this regard. First, NTF performance for partial years 1 to 3 was modeled, using data determined in this study. Effluent ammonia-N was calculated following the zero-order/first-order method of Gujer and Boller (1986) (see also WEF MOP#8 (Krause, 2010)), with the zero-order nitrification rate calculated based on the influent mass load (i.e., Figure 3b); results are shown (comparative with actual data) in Figures 4a–4c. Values for the transition to first-order kinetics were obtained from Table 3. For years 1 and 3, when the influent NH_3 concentration and load was relatively low, as shown (Figures 4a, 4c) only NTF1 was necessary to remove the ammonia; not requiring NTF2 is consistent with actual process observations (Figures 1a, 1c). Specifically examining year 1 data (Figure 4a), the modeled results were nearly the same as the actual results, although the model did predict slightly lower ammonia-N concentrations on select days. In contrast, modeled results in year 3 (Figure 4c) consistently showed much lower effluent ammonia-N concentrations for the first 13 days; thereafter, the model aligned well with the actual results, albeit again predicting slightly lower effluent values. These results suggest that for the first 13 days of this modeled period, the biofilm was still developing, and thus could not fully nitrify; the need for NTF2 for this same period (Figure 1c) would support this conclusion. Finally, considering year 2 data, when both NTF1 and NTF2 were required to achieve the desired treatment (due to the much higher applied ammonia-N load, Table 1), the model predicted somewhat conservative effluent values for both NTF1 and NTF2 (Figure 4b). Overall, NTF performance using the parameters developed in this study confirmed that the Gujer and Boller (1986) model would be a useful tool in the design and analysis of a full-scale NTF.

As a second assessment on the value of this study, the original pilot NTF design was re-evaluated (based on the original influent design criteria) applying the parameters derived herein. Two approaches were taken in this posthumous assessment. The first approach followed the simplified method detailed by Albertson and Okey (1989) that is also recommended by Krause et al. (2010) and that employs a simplified version of equation (1). The second approach employed equations derived by Gujer and Boller (1986) (consistent with the modeling assessment described above) that are based on equation (1). Both approaches utilized parameters established in this study. An $r_{n(0)}$ value of $2.24 \text{ g N/m}^2 \cdot \text{d}$ was obtained from Figure 3b for the original design influent ammonia load. For both methods, zero-order kinetics were assumed to predominate until the NH_3 concentration was reduced to 4 mg/L , below which first-order kinetics prevailed. Applying method one, the volume of media required for the zero-order zone was calculated at 4.1 m^3 . Under first order NH_3 removal, method one would recommend an additional 1.64 m^3 of NTF media. Thus, the total number of

NTF media modules (size as used in this pilot unit) required by applying method one would be 13. Applying design method two, the volume of media required for the zero-order zone was calculated at 4.6 m³, while first order NH₃ removal would demand an additional 1.15 m³ media. In total, again 13 NTF media modules would again be required. For method two analyses, a K_n of 1.5 mg N/L was assumed, along with a k value of 0.4 m⁻¹. Comparatively, the revised designs would reduce the media requirements over the original design by 19% (3 NTF media modules). Not only did the pilot-scale operations refine the zero- to first-order transition concentration, but the maximum rate of NH₃ removal was significantly higher than originally estimated as was the removal rate decay within the first-order zone.

Conclusions

Research presented and discussed herein focused on the analysis of pilot-scale data for a potential future full-scale nitrifying trickling filter that would treat effluent from the city of Colfax, WA aerated lagoon system. Key conclusions from this research are as follows:

- An NTF would be a very effective and reliable method of NH₃ removal in treating aerated lagoon effluent, and it is reasonable that an NTF could produce effluent NH₃ concentrations less than 1.0 mg/L. A two-in-series NTF operation is recommended over a similar sized single NTF.
- NTF performance was characterized by both zero- and first-order NH₃ removal regimes. Zero-order nitrification rates correlated with influent NH₃ mass loading in a statistically significant manner, with rates increasing substantially as NH₃ mass loading increased.
- NTF operation does appear sensitive to cold temperatures, with biofilm development and associated NH₃ removal requiring extended periods to establish. For only part-year NTF operations, temperature should be monitored to establish the proper time for NTF start-up.
- Design guidance and kinetic parameters presented in WRRF design manuals is conservative, and the NTF literature provides only limited data on the internal NTF ammonia removal kinetics. For Colfax, by applying data derived from the pilot-scale operations, the size of the NTF could be reduced by approximately 19%. Moreover, modeled NTF performance using data developed in this study well predicted effluent ammonia-N concentrations.
- Pilot NTF kinetic data has been evaluated within the context of current NTF modeling theory to provide a data set that could be useful to engineers designing full-scale NTFs to minimize excess conservativeness without the need of pilot-scale testing.

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