Trickling Filter Nitrification Performance Characteristics and Potential of a Full-Scale Municipal Wastewater Treatment Facility

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Abstract: The trickling filter solids contact water pollution control facility for the city of Ames, Iowa has successfully nitrified wastewater with trickling filters for the past decade. Both first stage, carbonaceous biochemical oxygen demand removing trickling filters (TFs) and second stage, nitrifying TFs (NTFs) remove significant quantities of ammonia from the wastewater. Based on operating data from January 1999 through December 2001, the average specific ammonia removal rate for the TFs was 1.5×10^{-4} kg N/(d m^2). Most probable number testing confirmed the presence of nitrifiers in the top media layer of both stages of trickling filters. An experiment was performed whereby flows to the TFs and NTFs were varied to test ammonia removal capabilities of the facility. During the experiment, the TFs removed an average of 2.4×10^{-4} kg N/(d m^2) and the NTFs removed an average of 1.5×10^{-5} kg N/(d m^2) due to low loading. Data collected during the study varied with operating conditions. It was compared to and used to calibrate NTF models. An empirical design model poorly fit the data, and a theoretically based model could not be calibrated well with apparent ammonia removal rates. A best-fit equation, dependent on hydraulic loading and influent ammonia concentration (adjusted for recirculation), was regressed directly to the data and is useful for describing nitrification in the Ames WPCF TFs.

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Introduction

Nitrification was initially believed to be merely an added benefit of treating wastewater with trickling filters (TFs). Eventually, TFs were designed as a tertiary treatment process for the sole purpose of nitrification based on empirical data. In 1975, the United States Environmental Protection Agency (U.S. EPA) published a series of empirical design curves for the design of nitrifying TFs (NTFs) as a function of influent ammonia concentration, desired ammonia removal, and temperature (Gullicks and Cleasby 1986). A number of theoretical models based on transport processes and diffusion limiting conditions for nitrification were also developed for the design of NTFs (Gujer and Boller 1986; Logan 1993; Rittman and McCarty 2001).

The Ames water pollution control facility (WPCF) had treated wastewater with rock media TFs since the 1960s. A new plant was to be constructed with NTFs. Gullicks and Cleasby (1990b) created a design methodology for aid in NTF development. Four operating variables, temperature, influent ammonia concentration, hydraulic loading, and recirculation, were believed to be important for ammonia removal in NTFs. During the initial study, data from the EPA's curves were reorganized into a new set of curves accounting for the variables that Gullicks and Cleasby (1986) felt were important. A pilot-scale study was then performed (Gullicks and Cleasby 1990a) to collect data specific to Ames' wastewater. Data from the pilot study and operating data from a number of full-scale facilities were incorporated into the design curves (Fig. 1). Ammonia removal is adjusted to a 10°C basis by the Nernst–Einstein equation, and recirculation was accounted for by adjusting influent ammonia concentration and hydraulic loading. The abscissa represents the recirculation adjusted hydraulic loading rate, and the ordinate is the recirculation adjusted influent ammonium concentration on a nitrogen basis. The influent ammonia concentration and hydraulic loading intersect the curves, which represent specific ammonia removal rates on a total media surface area basis.

The TF solids contact Ames WPCF (AWPCF) was designed for an annual average ammonia loading of 894 kg N/day, and currently receives an ammonia loading of 454 to 635 kg N/day. Two TFs and two NTFs were built measuring 24.4 m in diameter with 7.92 m of media depth. Both stages operate in a parallel flow scheme, and the TFs in each stage cannot be changed to operate in series. The TFs contain plastic 60° crossflow media with a specific surface area of 98.4 m^2/m^3, and the NTFs contain plastic 60° crossflow media with a specific surface area of 164 m^2/m^3. Natural draft air circulation is used during the winter and forced

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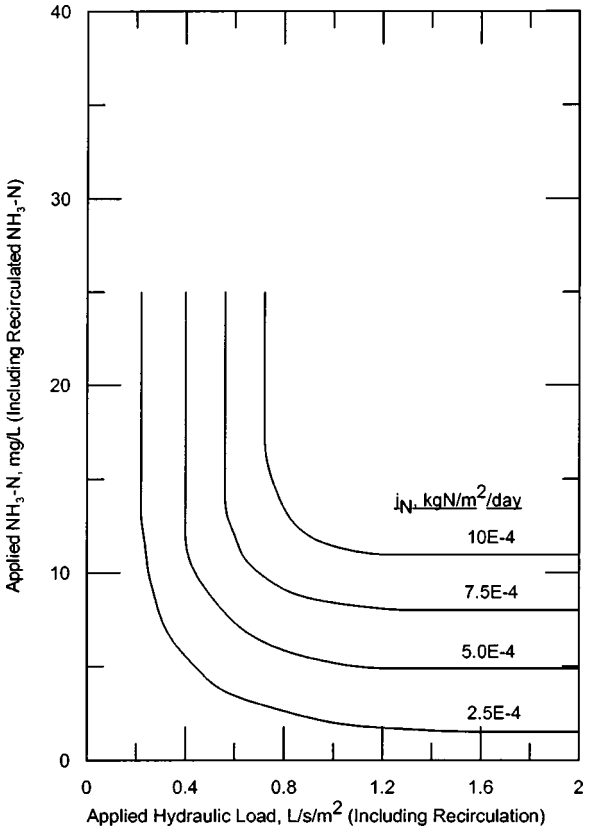

Fig. 1. Replication of Gullicks and Cleasby (1990b) design curves of ammonia removal at 10°C. Used by permission of the Water Environment Federation, Alexandria, Va.

draft during the spring, summer, and fall. A solids contact process separates the two stages of TFs (Fig. 2). The AWPCF went into partial operation in May 1989, and full operation began on November 16, 1989.

A number of general statements can be made about the mechanisms for nitrification in TFs. Nitrification is the conversion of ammonia to nitrate by aerobic autotrophs. An ammonia substrate is needed, oxygen must be available, and an inorganic carbon source should be available. Alkalinity is needed since it is consumed as the carbon source during nitrification.

Specific observations have been made with respect to nitrification in TFs. Nitrification in TFs is generally either oxygen flux limited or ammonia flux limited. The limiting conditions depend on the diffusion constants for oxygen and ammonia, their respective molecular weights, the stoichiometry of the metabolic reactions, and the concentrations of oxygen and ammonia in the bulk liquid. Concentrations of ammonia above 4.0 mg N/L were found to lead to oxygen flux-limiting conditions and below 4.0 mg N/L lead to ammonia flux-limiting conditions (Gullicks and Cleasby 1986). Dissolved oxygen levels were found to be vital for nitrification in oxygen flux-limiting conditions (Gullicks and Cleasby 1990a). Also, an applied hydraulic loading rate (with recirculation) greater than 0.8 L/m^2/s had a negative impact on cold-weather nitrification, and the cold-weather effects of carbonaceous biochemical oxygen demand (CBOD) were more noticeable at low hydraulic loadings (Gullicks and Cleasby 1990a).

Many other parameters affect nitrification in TFs. The suspended solids and organics concentration should be low (Gullicks and Cleasby 1990b; Andersson et al. 1994). Wastewater temperature affects water and biofilm diffusion constants, bulk liquid film thickness, dissolved oxygen saturation concentration, and nitrification kinetics. The ammonia removal rate may be adjusted for temperature by the using the Nernst–Einstein equation. Some researchers concur with this type of temperature adjustment. They believe that if temperature is accounted for in a model, it should be in terms of diffusivity (Okey and Albertson 1987). Other researchers have observed a stronger correlation with media configuration and temperature (Logan and Parker 1990).

Theoretical and empirical models have been developed to design or predict ammonia removal in NTFs. Okey and Albertson (1989) developed an empirical equation that predicts ammonia removal by accounting for oxygen and ammonia flux-limiting conditions. Logan's model (1993) numerically solves for the maximum oxygen transport in a NTF, and is appropriate for oxygen flux-limiting conditions. The model has been written into a *FORTRAN* program to aid in design. Gujer and Boller (1986) developed a series of theoretical equations that explain the mechanisms for nitrification in a trickling filter. They then created an empirical equation that approximates the results of the theoretical equations and is integrated across the depth of a TF. An additional term was added as an option to account for decreased ammonia removal as a function of depth. Parker et al. (1989) explored the Gujer and Boller model further. It was reasoned that the maximum ammonia removal rate observed in the TF is a function of an efficiency term and the maximum oxygen flux.

Based on the needs of the AWPCF, goals were developed for this research as follows:

(1) Determine the nitrification performance capabilities of the AWPCF's TFs and NTFs.

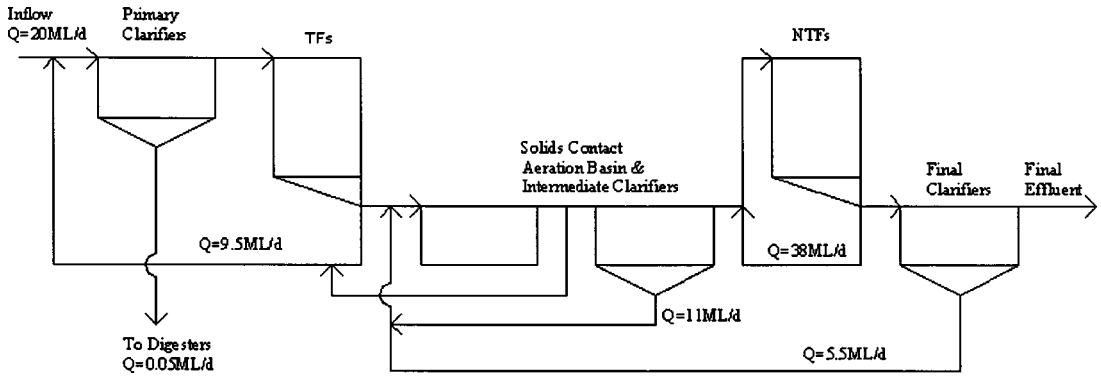

Fig. 2. Ames water pollution control facility flow scheme

(2) Determine the effects of operating variables, temperature, and recirculation ratio on ammonia removal in both the TFs and NTFs.

Reviewing literature, Gullicks and Cleasby's original research, and the AWPCF operating data led to the following hypotheses:

(1) Noting the nitrifying capabilities of the TFs, it was hypothesized that CBOD and ammonia may be removed simultaneously in the TFs at the AWPCF.
(2) The AWPCF TFs remove ammonia as predicted by Gullicks and Cleasby's (1990b) design curves and hence nitrification is dependent on hydraulic load, ammonia influent concentration, recirculation, and temperature.
(3) The Gujer and Boller (1986) model employs these key operating variables, based on theoretical concepts, and may be calibrated to extrapolate ammonia removal in the TFs and NTFs of the AWPCF.

Materials and Methods

Operating data from January 1999 through March 2002 were analyzed. The specific ammonia removal rates in the TFs were determined, but were low or unknown for NTFs since most concentrations were below detection limits. The data were analyzed for a correlation between ammonia removal and organics loading, temperature, and time of year. Trends and anomalies were sought.

An experiment was designed to prove or disprove the hypotheses listed and complete the goals of this study. The TFs are exposed to the entire ammonia loading on the plant allowing for maximum ammonia removal performance. The NTFs, however, receive a small fraction of the overall ammonia loading, typically less than 32 kg N/day, due to nitrification in both the TFs and the solids contact process. The flow scheme at the AWPCF was changed to augment the ammonia loading on the NTFs. The NTFs were temporarily switched with the solids contact aeration basin in the flow scheme, to increase the ammonia load on the NTFs. The ammonia load on the NTFs increased to between 45 and 68 kg N/day for the study, and the $CBOD_5$ concentration was typically less than 5 mg/L.

The ammonia influent concentration naturally varies on a day to day basis at the facility. Recirculation of digester supernatant augments and causes additional variability in the influent ammonia concentration. The wastewater flow into the TFs is held nearly constant by recirculation. The hydraulic loading to the TFs was varied manually for one month during the study, and samples were taken after the flows stabilized. The parallel flows to each TF stage were manipulated by adjusting sluice gates in the splitter box. One sluice gate was lowered at different levels for both TFs and NTFs to adjust the hydraulic loading. During the study, the TF flow fraction was changed from 50/50 to 60/40 to 66/34 so that one would receive a high flow while the other was at low flow. A pan test was used to verify the flow distribution between the TFs. Average flows are shown in Table 1.

Grab samples were taken three to five times per week from the influent and the effluent of the TFs. Influent samples were taken directly from the top of the TF media by placing a two liter beaker on the media to capture the wastewater after it flows from the distributor. Effluent samples were taken from the collection channel at the bottom of the trickling filters by dipping a two liter beaker into the channel. Samples were chilled on site by placing them into a cooler, and they were refrigerated in the lab. They were then tested for ammonia concentrations within 24 h, or preserved and tested within one week as indicated in Standard Methods [American Public Health Association (APHA) et al. 1995]. Flow weighted composite samples collected by the AWPCF have also been used in the study. A number of the samples were tested for nitrates to confirm nitrification. The nitrogen balance was completed by testing samples for total Kjeldahl nitrogen (TKN).

Table 1. Average Flows in Ames Water Pollution Control Facility Trickling Filters during Test

Period	Trickling filter	Flow (10^6 L/day)
I (50/50)	TF 1	14.2
	TF 2	14.2
	NTF 1	32.7
	NTF 2	32.7
II (60/40)	TF 1	17.1
	TF 2	11.4
	NTF 1	39.3
	NTF 2	21.2
III (66/34)	TF 1	18.8
	TF 2	9.7
	NTF 1	43.2
	NTF 2	22.3

Note: TF=trickling filter; and NTF=nitrifying TF.

$CBOD_5$, chemical oxygen demand (COD), pH, and ammonia were all measured as suggested by Standard Methods (APHA et al. 1995). Probes were used to measure ammonia and pH. Nitrates were measured using ion chromatography on Dionex Equipment (Sunnyvale, Calif.) consisting of a conductivity detector (CD20), gradient pump (GP40), suppressor (ASRS Ultra 4 mm), column (AN300), and an auto sampler (AS40). Data were recorded onto a personal computer with the Dionex Peaknet Chemo workstation. TKN was measured by the analytical services laboratory within Iowa State University's Civil and Construction Engineering Department using an auto analyzer with spectrophotometry. The difference between influent TKN and ammonia was assumed to be organic nitrogen that could be ammonified through the plant processes. Operating data included measurements of total daily flow, $CBOD_5$, total suspended solids, volatile suspended solids (VSS), ammonia, wastewater temperature, and waste solids flows and concentrations. COD estimates for TF operating data have been calculated based on the actual CBOD concentrations using ratios of 2.2 and 3.0 mg COD/mg CBOD for influent and effluent, respectively, which were determined during the experimental phase of the study. The soluble effluent COD was then calculated using the measured VSS with a ratio of 1.42 mg COD/mg VSS.

The data used for the analysis were operating data from the facility, and data from the experimental phase of the study. For the TFs, 355 operating data points and 27 experimental data points were catalogued and used for the calibrations. Experimental observations yielded 48 data points for the NTFs. Data were compared to the design curves, used to calibrate the Gujer and Boller (1986) model, and used to develop an empirical equation for ammonia removal predictions. Ammonia removal was calculated as the observed change in ammonia through the TF on a specific basis or per total media surface area. The removal has been converted to a 10°C basis by multiplying it by the diffusion coefficient for oxygen in water at 10°C and dividing by the diffusion coefficient for oxygen at the actual wastewater temperature (Gullicks and Cleasby 1990b). Diffusion was determined using the Nernst–Einstein equation:

$$D_{O,T} = \frac{CT}{\mu_{H_2O}} \quad (1)$$

The adjustment reduced the observed ammonia removal at temperatures higher than 10°C to lower values.

A linear fit was used for comparing nitrates generated versus ammonia consumed. If the slope is one, nitrogen conversion is complete. A negative effect of organics on the specific ammonia removal rate in the TFs was also tested by a linear fit. The null hypothesis for linear fits is that the slope is zero, and the alternative hypothesis is that the slope is not zero. Slope significance was therefore determined by comparing the p value to the significance level, or alpha value assumed to be 0.05 for the analyses. All statistical regressions were performed using the statistical software *JMP* (2002). Values of R^2 were used to value the strength of the fit.

Gullicks and Cleasby's design curves (1990b) were approximated by an equation to allow for a statistical analysis. The following best-fit equation was found to give the best representation of Gullicks and Cleasby's design curves:

$$j_N = -0.000\,41 + 0.0011\nu_H + 4.9 \times 10^{-5} S_{N,i} - 0.000\,46\nu_H^2 + 3.4 \times 10^{-5} S_{N,i}\nu_H - 2.0 \times 10^{-6} S_{N,i}^2 \quad (2)$$

The equation is appropriate for the range of data shown by the design curves (Fig. 1). The Gujer and Boller model (1986) without an empirical depth parameter is

$$\frac{zaj_{N,\max}}{\nu_H} = S_{N,i} - S_N + N \ln\left(\frac{S_{N,i}}{S_N}\right) \quad (3)$$

It can be manipulated to solve the observed specific removal in terms of the influent ammonia concentration and hydraulic loading in the same manner as Gullicks and Cleasby's design curves (1990b):

$$S_{N,i} = \frac{1{,}000\dfrac{\text{mg m}^3}{\text{kg L}} azj_N}{\left(86.4\dfrac{\text{s m}^3}{\text{d L}}\nu_H\right)\left[1 - \exp\left(\dfrac{1{,}000\dfrac{\text{mg m}^3}{\text{kg L}}(j_N - j_{N,\max})az}{N\left(86.4\dfrac{\text{s m}^3}{\text{d L}}\nu_H\right)}\right)\right]} \quad (4)$$

Note that as j_N departs from $j_{N,\max}$, the exponential term approaches zero. Hence, Eq. (4) simplifies to

$$j_N = \frac{S_{N,i}\left(86.4\dfrac{\text{s m}^3}{\text{d L}}\nu_H\right)}{1{,}000\dfrac{\text{mg m}^3}{\text{kg L}}az} \quad (5)$$

For a particular TF, the media depth and specific surface area will be constant. Thus, the specific ammonia removal rate will be dependent on the ammonia influent concentration and the hydraulic loading when the TFs are not operating near the maximum specific ammonia removal rate.

To calibrate the Gujer and Boller model (1986), data were fit to Eq. (4) using a nonlinear regression function. Calibration of the Gujer and Boller model is specific to the characteristics of a TF. The TFs and NTFs were therefore calibrated separately using the operating data. The Gujer and Boller model is intended for TFs after secondary treatment (Gujer and Boller 1986) and is more appropriate for the NTFs. Due to its theoretical basis, the model is suitable for extrapolating beyond the range of the data.

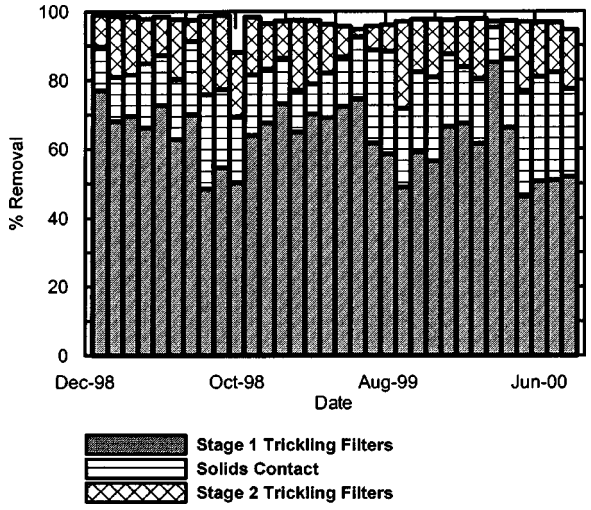

Fig. 3. Percentage ammonia removal in Ames water pollution control facility biological treatment processes

A best-fit equation was regressed directly to the data in terms of hydraulic loading, influent ammonia concentration, and the specific ammonia removal rate adjusted to 10°C to improve predictions. Since the best-fit equation was regressed to the data, it is not appropriate for extrapolation. The best-fit regression equation and the Gujer and Boller model were used to evaluate performance of the TFs for design ammonia loading. Significance of the models was determined statistically using R^2 values and the coefficient of variability:

$$C_v = \frac{\text{SD}}{\bar{x}} \quad (6)$$

A lower coefficient of variability indicates a better fit.

Statistical F-tests were performed on the regression equations and the parameters of the equations to verify significance of fit. The overall F-test establishes if the equation as a whole has significance, and the partial F-tests impart significance of individual terms in the equation (Kleinbaum et al. 1998). The null hypothesis is that either the equation or the individual terms are not significant, and the alternative hypothesis is that they are significant. *JMP* (2002) was used to generate p values, which can be compared to a chosen significance level or alpha. An alpha value of 0.05 was chosen, and when the p value is less than 0.05 the null hypothesis is rejected in favor of the alternate hypothesis; i.e., the equation or terms are significant at a 95% level of confidence.

In order to determine whether ammonia removal occurs simultaneously with CBOD removal or at lower depths after CBOD removal in the TFs, it is useful to know ammonia concentrations along the depth profile. Unfortunately, sampling ports were unavailable to acquire samples at intervals along the TFs. A most probable number (mpn) test for nitrifiers was performed as an alternative way to verify or disprove the existence of nitrifiers. Biofilm samples were scraped from the top of the media in one of the TFs and one of the NTFs. The biofilm from the top of a trickling filter was scraped from a number of random spots and mixed together to give a composite biofilm sample. An mpn test was performed on the biofilm samples. The mpn test was performed in accordance to the method listed by Schmidt and Belser

Table 2. Typical Range of Ammonia, Nitrate, and Total Kjeldahl Nitrogen (TKN) Concentrations (mg N/L) at Ames Water Pollution Control Facility during Normal Operation

	Trickling filters		Solids contact		Nitrifying trickling filters	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
Ammonia	16–23	3–9	3–9	1–3	1–3	<0.5
Nitrates	2–5	12–17	12–17	22–27	22–27	25–30
TKN	25–32	13–18	13–18	4–6	4–6	2–3

(1994). A recipe for nitrifier media is given by the method, and nitrifiers were identified by the presence of either nitrites or nitrates using an ion chromatograph after six weeks of incubation. Serial dilutions of 10^{-1} through 10^{-10} were used since the approximate number of nitrifiers was not known.

Results

The operating data were used to show which processes were removing ammonia in the facility. The data show that the TFs remove the largest fraction of ammonia in the facility (Fig. 3). The solids contact process also removes a significant amount of ammonia. The NTFs remove only a small percentage of the current overall ammonia load. On average, the TFs remove 63%, the solids contact process removes 20%, and the NTFs remove 14%.

The nitrogen mass balance was completed by measuring ammonia, TKN, and nitrates in the TFs. Typical values for ammonia, TKN, and nitrates during normal operation are listed (Table 2). A plot has been created that shows (Fig. 4) nitrates generated versus ammonia consumed on a nitrogen basis. The slope of the curve should be 1.0 if all ammonia lost is being converted to nitrates. The slope is 1.1 mg NO_3^-—N/mg NH_3—N, which may be explained by experimental error or organic nitrogen undergoing ammonification and subsequent nitrification. Based on TKN testing, it appears that roughly 1 to 2 mg N/L of soluble organic nitrogen is ammonified in the TFs and about 0.5 mg N/L is ammonified in the NTFs. The unexplained nitrates may be from ammonification and subsequent nitrification of organic nitrogen, however, most ammonification appears to occur in the solids contact process. The observed ammonia removal rates are an underestimate of the total ammonia removal if the ammonia resulting from ammonification is neglected.

The relationship between COD concentrations and the specific ammonia removal rates in the TFs was studied in detail to estimate the effect of organics and, consequently, heterotroph competition on nitrification in TFs (Fig. 5). Strangely, a weak positive linear effect of influent soluble COD concentration on ammonia removal was found to be significant (results not shown). This analysis fails to take into account that an increase in influent soluble COD is usually accompanied by an increase in influent ammonia concentration. On the other hand, a weak negative linear effective on the specific ammonia removal rate accompanying an increase in effluent soluble COD was found significant:

$$j_N = 0.000\,420 - 5.50 \times 10^{-7} S_{\mathrm{COD},e} \tag{7}$$

The R^2 for the effluent COD comparison was found to be only 0.05, however, the equation has a small slope. Based on the slope, an increase in the effluent soluble COD of 76 mg/L would be required to decrease the specific ammonia removal rate by 10%.

Nitrifiers were found to exist in the top of the TFs and NTFs based on mpn test results. The mpn of nitrifiers for the top media layer in the TFs found 3,000 (ammonium and nitrite oxidizers) per gram of dry biofilm. The mpn of nitrifiers for the top layer of media in the NTFs found 31,800 (ammonium and nitrite oxidizers) per gram of dry biofilm. The number of nitrifiers found is similar to that of unfertilized soil, which would be between 10^3 and 10^4 per gram of dry soil (Sylvia et al. 1999).

Operating data for the AWPCF TFs were plotted and compared to the Gullicks and Cleasby curves (1990b) (Fig. 6). The effluent ammonia concentration for the NTFs is below the 0.5 mg N/L detection limit for the AWPCF laboratory, therefore, the operating data in Fig. 6 is reflective of only the TFs. The TFs normally operate at a constant hydraulic loading near 0.4 L/s/m^2 as seen in the plot of Fig. 6. For the data above 0.4 L/s/m^2, however, the Gullicks and Cleasby-type curve shape begins to emerge. The

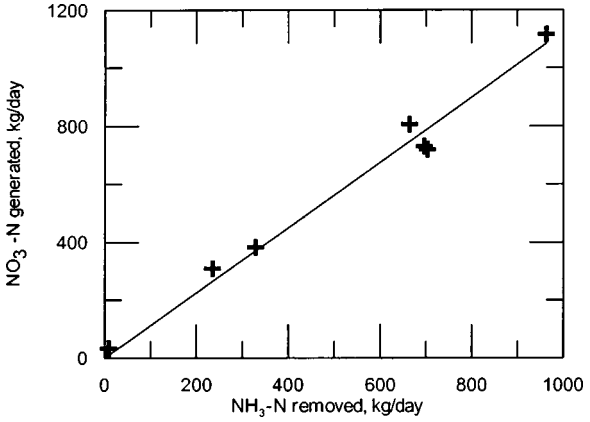

Fig. 4. Ammonia removed versus nitrates generated in trickling filters and nitrifying at Ames water pollution control facility

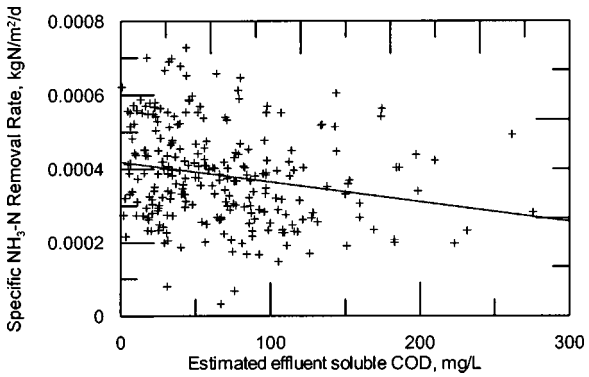

Fig. 5. Relationship between ammonia removal and soluble carbonaceous biochemical oxygen demand concentration in trickling filters

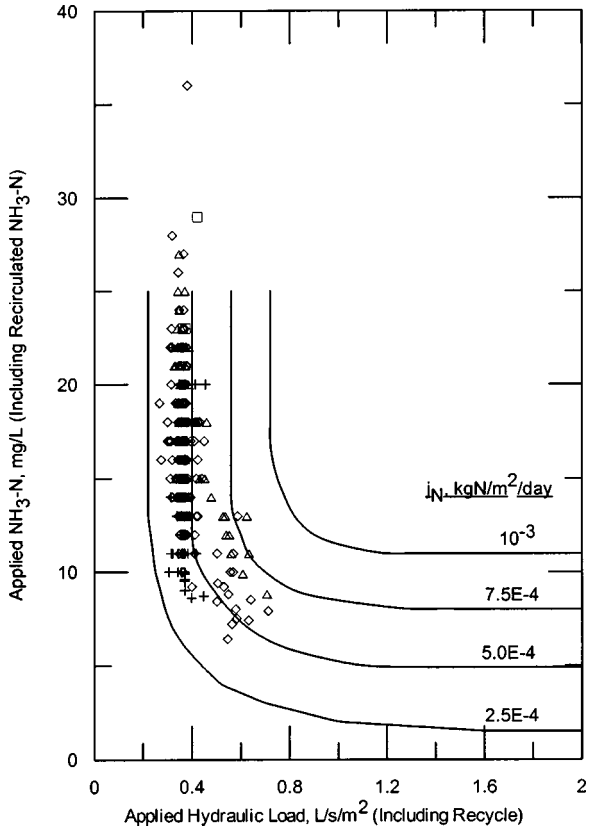

Fig. 6. Operating data from the Ames water pollution control facility trickling filters superimposed over a replication of Gullicks' design curves. $+ = 0$–2.5×10^{-4} kg N/m^2/day; $\diamond = 2.5$–5.0×10^{-4} kg N/m^2/day; $\triangle = 5.0$–7.5×10^{-4} kg N/m^2/day; and $\square = 7.5$–10.0×10^{-4} kg N/m^2/day.

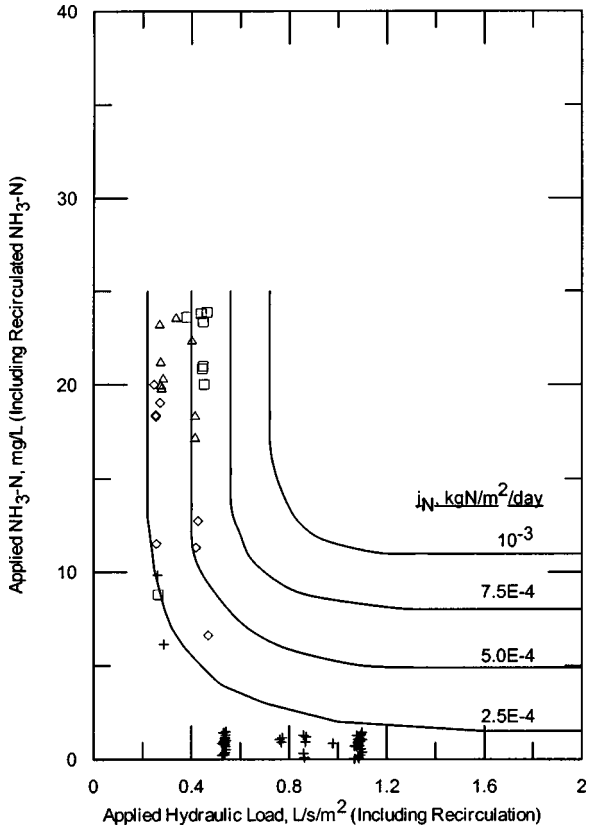

Fig. 7. Experimental data from Ames water pollution control facility trickling filters (TFs) and nitrifying TFs superimposed over a replication of Gullicks' design curves. $+ = 0$–2.5×10^{-4} kg N/m^2/day; $\diamond = 2.5$–5.0×10^{-4} kg N/m^2/day; $\triangle = 5.0$–7.5×10^{-4} kg N/m^2/day; and $\square = 7.5$–10.0×10^{-4} kg N/m^2/day.

data poorly fit the curves based on a statistical comparison with the Gullicks and Cleasby curve approximation resulting in a coefficient of variability of 1.06.

Experimental data from the AWPCF study were plotted and compared to the Gullicks and Cleasby curves separately (Fig. 7). Influent ammonia concentrations for the TFs can be observed above 5 mg N/L and below 5 mg N/L for the NTFs. It can be generally seen that the curves are, as intended, a conservative basis for cold-weather design. For example, the specific ammonia removal data for the range of 7.5E-4 to 10.0E-4 kg/m^2/day lie between the region of the curves that predicts a removal between 5.0E-4 to 7.5E-4 kg/m^2/day. The 75 experimental data points poorly fit the Gullicks and Cleasby curve approximation with an R^2 of 0.55 and a coefficient of variability of 0.86.

The TF experimental and operating data, 382 points, were fit to the Gujer and Boller model (1986). Global minima were found for the resulting equation which had a negative R^2 (poor fit of a nonlinear equation) and coefficient of variability of 0.49 (Fig. 8). The calibration for the NTFs used 48 data points from the experimental phase, but due to the limited data, the regression would not converge at reasonable values for the constants. The values suggested by Gujer and Boller were, therefore, used to evaluate potential ammonia removal rates in the NTFs (Fig. 9). Model calibrations can be found in Table 3.

A best-fit equation was regressed directly to the operating and experimental data:

$$j_N = 7.65 \times 10^{-5} S_{N,i} v_H \tag{8}$$

The R^2 for this equation is 0.56 with a coefficient of variability of 0.30. The plot of Eq. (8) (Fig. 10) shows a moderate fit to the data. Empirical data came from AWPCF TFs and NTFs and Eq. (8) may be applied to those TFs. Most of the data used to generate this model, however, are from the TFs, and this model is most appropriate for use when predicting ammonia removal in the TFs within the range of the data used to regress the empirical equation. Use of the equation also assumes that external conditions, variables not accounted for in the equation, remain similar to those for which the data were collected.

Eq. (8) is reminiscent of Eq. (5) where the specific ammonia removal rate is dependent on only the product of a constant, influent ammonia concentration, and the hydraulic loading. Note that the average specific ammonia removal rate for the TFs is about 10% of the calibrated maximum specific ammonia removal rate from the Gujer and Boller model (1986), which reduces the exponential term from Eq. (4) to 0.08. If the depth and specific surface area for the TFs are substituted into Eq. (5), the coefficient becomes 1.11×10^{-4}. If the depth and specific surface area for the NTFs are substituted into Eq. (5), the coefficient becomes 6.65×10^{-5}.

The models were used to predict ammonia removal at the AWPCF for design loading conditions (Table 4) with no recirculation in the TFs or ammonia removal in the solids contact process. Average annual loading during the design year for ammonia is 900 kg N/day at a flow of 32.5×10^7 L/day, resulting in an

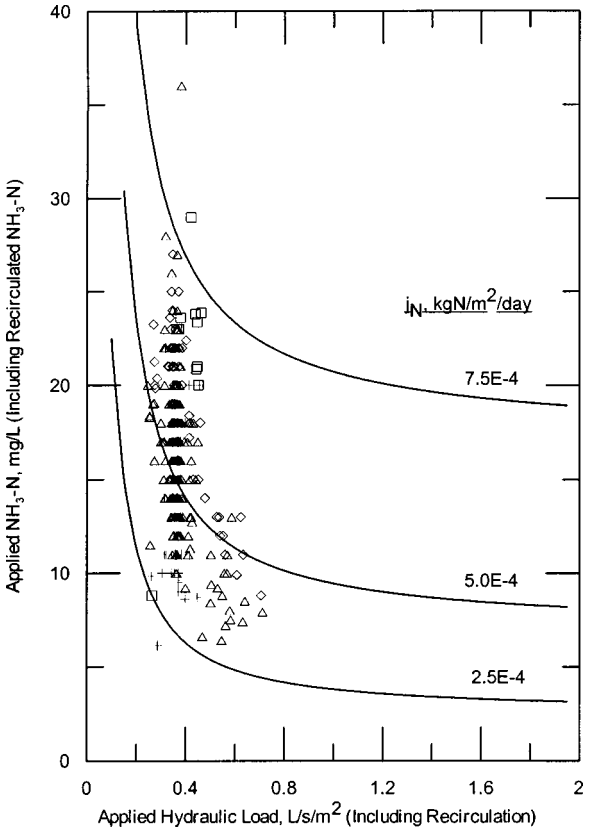

Fig. 8. Experimental and operating data from the trickling filters were used to calibrate the Gujer and Boller model (1986). +=0–2.5 $\times 10^{-4}$ kg N/m^2/day; ◇=2.5–5.0$\times 10^{-4}$ kg N/m^2/day; △=5.0–7.5$\times 10^{-4}$ kg N/m^2/day; and □=7.5–10.0$\times 10^{-4}$ kg N/m^2/day.

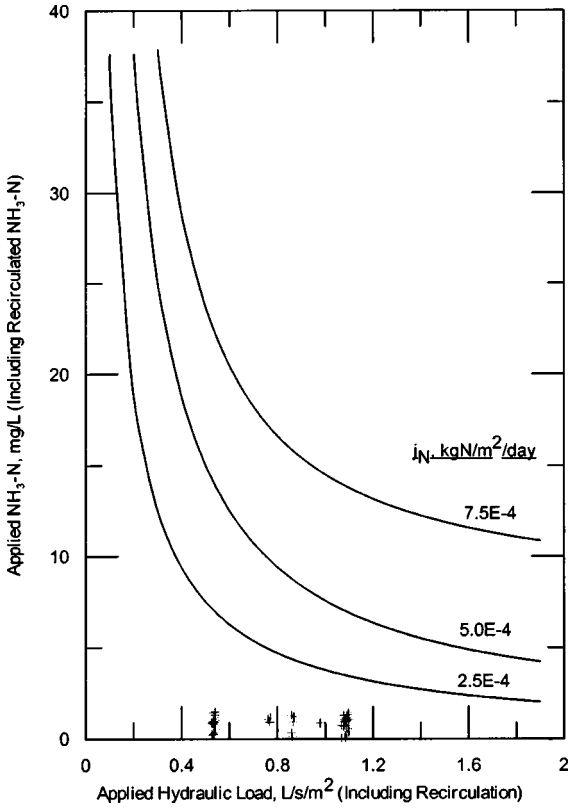

Fig. 9. Experimental data from the nitrifying trickling filters is compared to the Gujer and Boller model (1986) with default parameters. +=0–2.5$\times 10^{-4}$ kg N/m^2/day; ◇=2.5–5.0$\times 10^{-4}$ kg N/m^2/day; △=5.0–7.5$\times 10^{-4}$ kg N/m^2/day; and □=7.5–10.0 $\times 10^{-4}$ kg N/m^2/day.

influent ammonia concentration to the TFs of 27.5 mg N/L. The models predict full ammonia removal at the facility at design loading conditions for nitrification occurring in both the TFs and NTFs.

Discussion

The data show consistently high ammonia removal rates in the TFs despite the high $CBOD_5$ load. Higher influent or effluent $CBOD_5$ concentrations, and consequently loading, do not have a negative linear effect on the percentage ammonia removal. The presence of nitrifiers in the top of the TFs was confirmed with an mpn test. The effect of $CBOD_5$ on nitrification in the TFs is negligible, nonlinear, or masked by other unaccounted effects.

Data collected for this study do not match the predicted performance from the design curves (Gullicks and Cleasby 1990b). The disparities may be due to the intended conservative nature of the curves, unaccounted factors, or fundamental flaws in the curves. First, a majority of the data is from the TFs, which are intended for $CBOD_5$ removal. A significant linear effect on ammonia removal was not correlated to $CBOD_5$, but the effect may have been hidden by confounding factors or been nonlinear. For example, an increase in influent $CBOD_5$ concentration is frequently accompanied by an increase in influent ammonia concentration at the AWPCF. It is difficult to determine if the curves have a fundamental flaw. Indeed, the design curves seem to follow a pattern not unlike the Gujer and Boller model (1986) except the curved section is sharper and the ends become parallel to the x and y axes instead of slowly approaching an asymptote. Operating data appear to follow the Gujer and Boller model in the curved region better, but data nearer the vertical end are inconclusive, while no data are available for the horizontal end. A number of different specific ammonia removal rates overlap for the same conditions, which suggests that some other variable resulted in an increased or decreased removal.

Gullicks and Cleasby's model has an R^2 of 0.55 for just the experimental data, but a negative R^2 when tested with the operating data. Eq. (8) has a R^2 for the operating and experimental data of 0.56. Interestingly, Gullicks and Cleasby's model includes

Table 3. Gujet and Boller Model Calibrations

Trickling filters	Data source	$j_{N,\max}$ (gN/m^2/day)	az (m^3/m^3)	N (mg N/L)	C_v	R^2
TFs	Operating and experimental data	1.14	777.36	8.9	0.49	<0
NTFs	Experimental data	0.85[a]	1,298.9	1.0[a]	0.27	0.67

Note: TFs=trickling filters; and NTFs=nitrifying TFs.

[a]Values suggested by Gujer and Boller (1986) were used because the data for the calibration were limited.

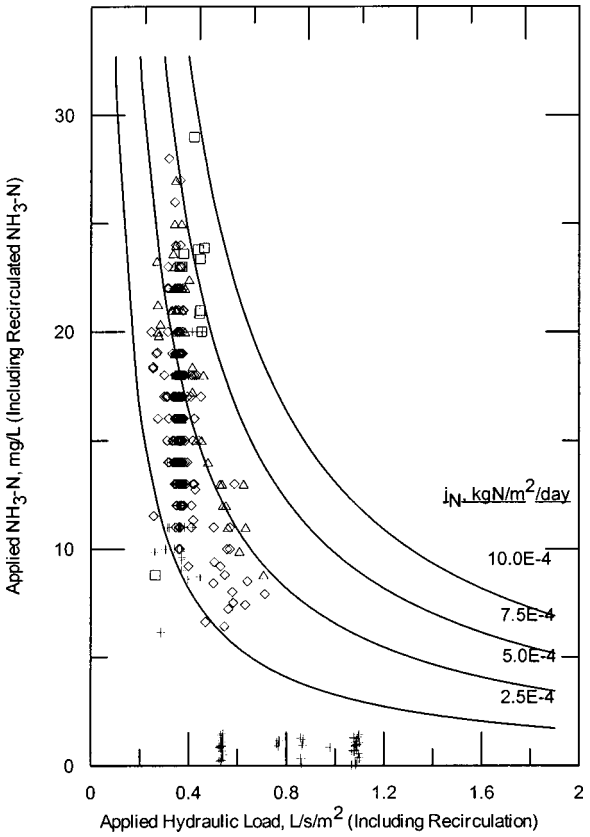

Fig. 10. Empirical regression [Eq. (6)] with operating and experimental data from the trickling filters (TFs) and nitrifying TFs. $+=0–2.5\times10^{-4}$ kg N/m^2/day; $\diamond=2.5–5.0\times10^{-4}$ kg N/m^2/day; $\triangle=5.0–7.5\times10^{-4}$ kg N/m^2/day; and $\square=7.5–10.0\times10^{-4}$ kg N/m^2/day.

an intercept term, which indicates that with no flow or loading the TFs will have a negative specific ammonia removal rate. The negative intercept is a result of the intended conservative nature of the model and is reflected in its poor fit.

The Gujer and Boller model poorly fits the TF data, and does not converge to the limited data for the NTFs. Gujer and Boller did not, however, intend for the model to be used for TFs with high organic loads (Gujer and Boller 1986). The NTF data are too limited to provide a fit to the model. Ammonia removal rates within the TFs, from sampling port data, would have given useful data that would have improved regression.

Four variables—influent ammonia concentration, hydraulic loading, recirculation, and temperature—have been relied upon as ammonia removal predictors in TFs. These variables were incorporated into all of the models used. The statistical tests for these models reveal how well these variables explain the variability in ammonia removal, and the correlation coefficient reveals how much of the variability was explained. Eq. (8) is the simplest test of the importance of these variables. It was found statistically significant and had an R^2 of 0.56 indicating that 56% of the variability in removal can be explained by the predictors. A number of data points have similar values for the predictor variables, but different ammonia removal rates as seen in Fig. 6 by the overlap of different ammonia removal rates. Factors responsible for these differences have not been discovered by this study.

Conclusions

The AWPCF NTF study helped accomplish the desired goals, supported a conclusion for the hypotheses of the study, and has ramifications for TF nitrification and future studies. The following conclusions resulted from the study:

- The models that are useful for predicting ammonia removal in the AWPCF TFs are the best-fit equation [Eq. (8)], generated from a statistical regression in this study, for the TFs, and the Gujer and Boller model (1986) for the NTFs. The default coefficients were used for the Gujer and Boller model, however, and a customized calibration would yield better predictions.
- It must be conceded that the first hypothesis, influent CBOD has no effect on nitrification, is not fully supported by the study. The evidence indicates that ammonia removal can be reliably high despite high CBOD concentrations, but this relationship at the AWPCF is poorly understood. Eq. (8) does a moderate job of explaining the variability in ammonia removal in the TFs. Part of the unexplained variability may be due to the effects of CBOD loading.
- The second hypothesis, the TFs at the facility remove ammonia as predicted by Gullicks and Cleasby's curves (1990b), appears to have been disproved. Gullicks and Cleasby's curves are actually a conservative basis for winter weather design, and it is shown from the analysis that Gullicks and Cleasby's curves, as intended by the authors, underpredict removal.
- Nitrification in TFs is a function of a number of variables. Given the appropriate model, the four operating variables listed as important in this study appear to explain a significant part of the variability of TF nitrification, as indicated by the correlation coefficient. A large part of the variability is, however, not accounted for. Either additional variables need to be considered, or the relationship used is not accurate.

The results from this study have implications for future studies. Specifically for the AWPCF, an improved calibration of the NTFs to a theoretical model should be performed by augmenting the ammonia load on the NTFs and installing sampling ports in order to observe the maximum ammonia removal and acquire data that reflect the effects of variables on ammonia removal. More generally, the phenomenon of simultaneous CBOD and am-

Table 4. Ammonia Effluent Predictions for Design Conditions at the Ames Water Pollution Control Facility

Process	Flow 10^6 (L/day)	Model	Influent NH_3 (mg N/L)	Effluent NH_3 (mg N/L)
Overall	32.5	—	27.5	0.0
Trickling filters	32.5	Eq. (8)	27.5	8.9
Solids contact[a]	32.5	—	8.9	8.9
Nitrifying trickling filters	62.4	Gujer and Boller (1986)	4.6	0.0

[a]Nitrification in solids contact neglected.

monia removal in TFs should be examined. Capital and operating costs could be cut considerably if a single stage TF system could be designed and optimized to perform both functions.

Notation

The following symbols are used in this paper:

a = specific surface area (m^2/m^3);
C = diffusion coefficient;
C_v = coefficient of variability;
$D_{O,T}$ = diffusivity of oxygen water at temperature (T), (cm^2/s);
$j_{COD,e}$ = effluent soluble chemical oxygen demand (COD) concentration (mg COD/L);
j_N = observed specific ammonia removal rate (kg $N/m^2/day$);
$j_{N,max}$ = maximum specific ammonia removal rate (kg $N/m^2/day$);
N = half saturation coefficient (mg N/L);
SD = standard deviation;
$S_{N,i}$ = ammonia influent concentration (mg N/L);
S_N = ammonia concentration (mg N/L);
T = absolute temperature (K);
x = mean;
z = depth of trickling filter media (m);
μ_{H_2O} = viscosity of water, centipoises; and
ν_H = hydraulic loading rate ($L/m^2/s$).

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