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Nitrification performance and potential at the Ames Water Pollution Control Facility

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Nitrification performance and potential at the

Ames Water Pollution Control Facility

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Environmental Engineering)

Program of Study Committee:
Timothy G. Ellis (Major Professor)
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Iowa State University

Ames, Iowa

2002

Graduate College
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This is to certify that the master's thesis of

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Signatures have been redacted for privacy

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ABSTRACT

The Ames Water Pollution Control Facility (AWPCF) treats wastewater generated by Ames' residents, industries, and Iowa State University. The current facility was designed by Rieke Carroll Muller Associates of Minneapolis, Minnesota. Dr. Harvey Gullicks, a former Iowa State University student, developed ammonia removal curves (Gullicks, 1987) that aided in the design of the facility's nitrifying trickling filters.

The AWPCF is currently underloaded with respect to ammonia and receives roughly half of the 1,970 lbNH$_3$-N/day that the facility was designed to treat. The facility removes ammonia to below the detection limit of 0.5 mgNH$_3$-N/L. The city personnel would like to know whether the facility can remove ammonia to concentrations below the permit requirements if the plant is subjected to design loading conditions or higher. As the result, a study of nitrification at the AWPCF was initiated.

Operating data coupled with data from an experimental study of the AWCPF were compared to Gullicks' original design curves, were used to calibrate the Gujer and Boller (1986) model, and were used to develop an empirical equation that predicts ammonia removal. The experiment required two major changes to the plant operations. The flow scheme at the AWPCF was changed to increase the ammonia loading on the second stage trickling filters, and the hydraulic loading on all trickling filters was varied to provide a treatment variable.

Examination of Gullicks' design curves and the Gujer and Boller model provides evidence that four major operating variables are important to ammonia removal in nitrifying trickling filters. Hydraulic loading, recirculation, ammonia influent concentration, and

temperature should be included or accounted for when predicting ammonia removal. The data from this study suggest that an empirical, two-variable quadratic model is most appropriate for predicting ammonia removal within the range of the operating and experimental data for the first stage trickling filters. The Gujer and Boller model is appropriate for the second stage trickling filters and extrapolating beyond the range of the data, but a calibration that includes a greater range of data is needed. Gullicks' design curves are useful as a design tool. All three models have been calibrated for AWPCF trickling filters, and application in other facilities should not be performed without checking assumptions and treatment conditions.

Based on model calibration, the AWPCF will be capable of removing ammonia at the design load given the operating conditions of this study. Though not designed for nitrification, the first stage trickling filters are removing a significant fraction of the ammonia load. The first stage trickling filters are assumed to follow the two-variable quadratic equation for removal given the organic load does not change; i.e. the external conditions for the experiment. Future studies on simultaneous treatment of biochemical oxygen demand (BOD) and ammonia in trickling filters to investigate the effect of the BOD to nitrogen ratio on nitrification, and to determine the depths at which nitrification occurs in the trickling filters are recommended.

CHAPTER 1. INTRODUCTION

Ammonia Effects

The treatment of a community's wastewater is important to conserve waterways and ensure a safe drinking water supply to downstream communities. Ammonia removal is an important part of any wastewater treatment system, as it can be harmful for three major reasons:

1.) It can be toxic to organisms in the waterway.

2.) Significant concentrations of ammonia lead to the eutrophication of lakes.

3.) Ammonia is an irritant to organisms at high concentrations.

Discharge requirements for a five day BOD (BOD_5) and total suspended solids (TSS) are dictated directly by the Environmental Protection Agency (EPA), but ammonia requirements are unique to each individual treatment plant. Permit limits for ammonia are governed by the National Pollution Discharge Elimination System (NPDES). Ammonia is generally removed in wastewater treatment facilities through biological nitrification whereby it is oxidized first to nitrite then immediately to nitrate. Effluent concentration requirements are higher for cold weather conditions since biological activity is reduced with lower temperatures.

Trickling Filters

The trickling filter is a common biological treatment system used for carbonaceous BOD (CBOD) and ammonia removal. Trickling filters contain a media over which a biofilm develops and matures. Wastewater flows across the biofilm and through the voids, and the microorganisms consume organics and nutrients that diffuse into the biofilm system. A plastic cross-flow media type is commonly used in trickling filters. Plastic cross-flow media are light in weight, high in strength, and provide a high specific surface area that allows the biofilm to efficiently treat the wastewater.

Nitrifying trickling filters were heavily researched during the middle 1980's through the early 1990's. Many theories were developed by biofilm researchers on the mechanism for ammonia removal through nitrification in trickling filter biofilms. Research was performed on laboratory and pilot scale systems, and in some cases full scale systems, to corroborate or refute these theories. The models and curves developed were then applied to the designs of modern day trickling filters and used to predict the performance of nitrifying trickling filters in operation.

Nitrification and Ammonification

Nitrification is a biological process that is an important part of the nitrogen cycle. Nitrification is the conversion of ammonia to nitrate in a two step process by two different genera of bacteria. The first step in the process is the conversion of ammonia to nitrite by *Nitrosomonas* bacteria. The second step in the process is the conversion of nitrite to nitrate

by *Nitrobacter* bacteria. The first step of nitrification is the rate limiting step and, therefore, nitrites are not usually observed during nitrification. The two reactions can be idealized by an overall reaction. The overall reaction is:

$$NH_4^+ + 1.83\ O_2 + 1.98\ HCO_3^- \xrightarrow{Nitrification} 0.02\ C_5H_7NO_2 + 0.98\ NO_3^- + 1.041\ H_2O + 1.88\ H_2CO_3$$
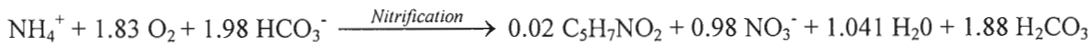
Ammonia can also be removed via physical and chemical means, such as adsorption, absorption, volatilization, and breakpoint chlorination. If the pH is above 9.3, the pK_a (negative log for the acid dissociation constant) for ammonia, volatilization may occur in the trickling filter. Nitrification, however, will be the most significant removal mechanism in most trickling filters. Nitrification can be verified by measuring nitrate production in the trickling filter. Nitrates may be converted to atmospheric nitrogen gas via denitrification in anaerobic conditions deeper in the biofilm when effluent containing nitrates is applied. If nitrification is the only mechanism for ammonia removal and there is no denitrification (the likely case for a well-ventilated trickling filter without effluent recirculation); all nitrogen from ammonia removed can be accounted for by nitrate production.

Nitrogen also exists in organic forms in wastewater. The nitrogen may be bound as organic compounds such as urea or within the cells of organisms as proteins. In the nitrogen cycle, organic nitrogen is converted to ammonia through ammonification. Ammonification is another part of the nitrogen cycle that may occur in trickling filters. Total Kjeldahl Nitrogen (TKN) is a measurement of all reduced forms of nitrogen in a sample, which would include ammonia and nitrogen in organic forms. The difference between the TKN value and the ammonia concentration gives an estimate of the concentration of organic nitrogen in a

sample. Changes in the organic nitrogen content of wastewater flowing through a trickling filter can therefore be accounted for by measuring the TKN and ammonia concentrations of influent and effluent samples. Nitrogen bound within organisms or particulates can be estimated by the volatile suspended solids (VSS) concentrations in the samples. Reduced nitrogen not accounted for by ammonia or VSS is from soluble organic compounds. A decrease in the reduced nitrogen associated with organic compounds indicates ammonification is occurring. Ammonia removal in a trickling filter is underestimated when not accounting for the ammonia resulting from ammonification.

History of the City of Ames Ammonia Removal System

The AWPCF has an excellent operating record, and the final effluent is of exceptional quality. CBOD and TSS concentrations are generally around 2 to 3 mg/L, and ammonia rarely exceeds the 0.5 mgN/L detection limit of their laboratory facilities. The operators are highly qualified ensuring the facility is operating within design guidelines and the processes are adequately treating the wastewater. Parameters (dissolved oxygen (DO) concentrations, pH levels, flow rates, pump motors, valves, etc.) not within proper tolerances are adjusted immediately.

The AWPCF utilizes plastic media trickling filters to remove organics and ammonia. The facility (Figure 1) has a separate stage process for nitrification, but nitrification occurs in all biological treatment steps. Wastewater is treated biologically in three steps. The first stage trickling filters (TF) were designed to remove CBOD. Wastewater then flows into the solids contact process where solids are controlled and further treatment is achieved. Finally,

the second stage, nitrifying trickling filters (NTF) were designed to polish the wastewater and
remove ammonia.
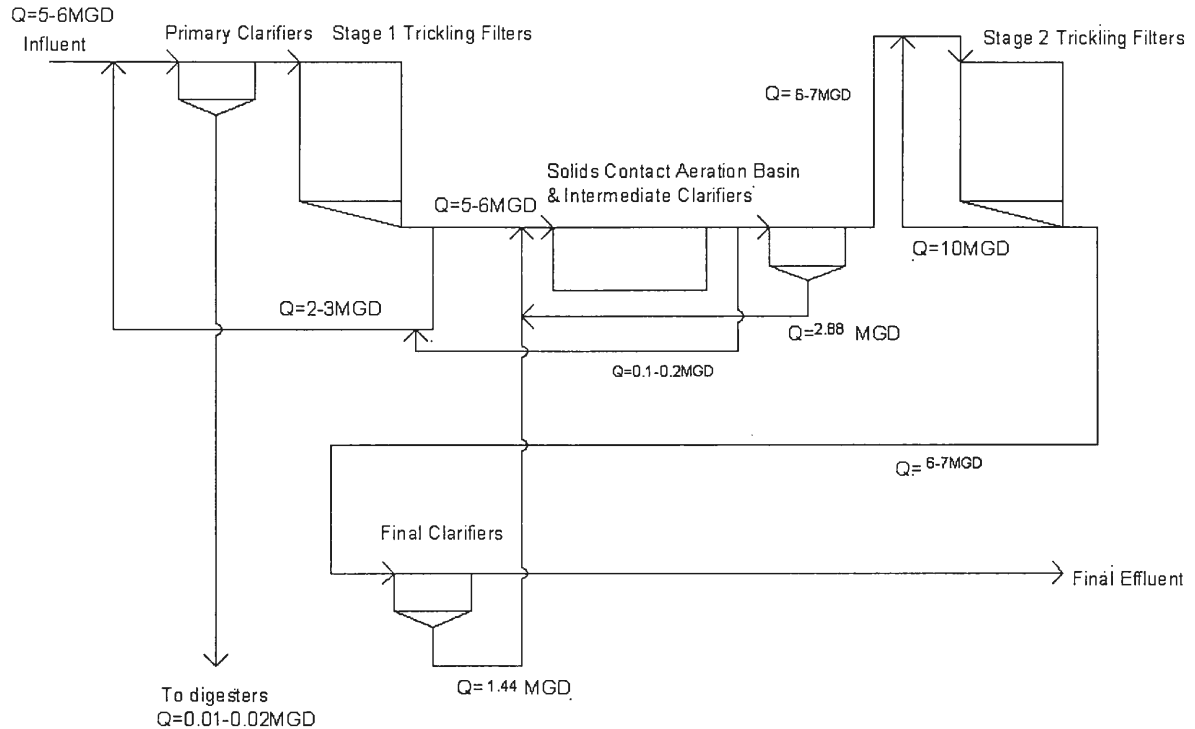
Figure 1. AWPCF flow scheme.

The AWPCF was designed with the aid of empirical design curves developed by
Harvey Gullicks as part of his doctoral studies under Dr. Jack Cleasby at Iowa State
University (Gullicks, 1987). Gullicks theorized that four critical operational variables affect
the performance of trickling filters. Hydraulic loading, wastewater temperature, influent
ammonia concentration, and recycle rate were all incorporated into the design curves.

Trickling filter design dimensions can be determined from the curves by applying the known or desired operating conditions and level of treatment required.

Gullicks' initial design curves were a modification of the EPA's empirical design curves based on pilot and full-scale data. The EPA design curves predicted the surface area required based on desired effluent concentration, wastewater temperature, and influent concentration. The EPA curves neglected hydraulic loading and recirculation. Gullicks reorganized the data into design curves that accounted for these neglected variables.

Gullicks later performed a pilot scale experiment in cooperation with the City of Ames (Gullicks and Cleasby, 1990a) to customize the design curves for Ames wastewater in cold climate conditions. A pilot scale trickling filter system was constructed at the former Ames Water Pollution Control Plant. Specific nitrification rates (on the basis of specific surface area, lbs/day/ft^2) were obtained from the pilot plant. Cold temperature empirical design curves were then developed from the data and adjusted to a 10°C basis using the Nernst Equation as described on page 16.

The current AWPCF was designed by Rieke Carroll Muller (RCM) Associates of Minneapolis, Minnesota. The design ammonia loading is 1,970 lbsN/day. The facility currently receives a typical ammonia loading of 1,000 to 1,400 lbsN/day. Maximum effluent ammonia concentrations have been established by NPDES requirements (Table 1).

Table 1. AWPCF ammonia effluent limits.

Type	Winter (Nov 1 – Mar 30)	Summer (Apr 1 – Oct 31)
Mean Monthly Limit	5.7 mg NH_3-N/L	3.3 mg NH_3-N/L
Mean Weekly Limit	8.6 mg NH_3-N/L	5.0 mg NH_3-N/L

Two TFs and two NTFs were built measuring 80 feet in diameter with 26 feet of media depth. Both stages operate in a parallel flow scheme, and each trickling filter in a stage cannot be changed to operate in series. The TFs contain plastic 60° crossflow media with a specific surface area of 30 ft^2/ft^3, and the NTFs contain plastic 60° crossflow media with a specific surface area of 50 ft^2/ft^3. The TFs and NTFs do not have motorized distributors. The trickling filter system maintains an excellent performance record (the facility has never had a permit violation) and was built below cost estimates. The trickling filters are operated with natural draft air circulation during the winter and forced draft during the summer. The AWPCF went into partial operation in May, 1989, and full operation began on November 16, 1989.

Trickling Filter Design Theory

Trickling filters were traditionally designed using empirical models such as the National Research Council (NRC), Germane-Shulz, or Modified Vels equation (Metcalf and Eddy, 1991). These equations offered a rough estimate of the amount of soluble CBOD

(sCBOD) that would be removed in the trickling filter. Ammonia removal was an added benefit and was not accounted for in the original models.

Eventually, the EPA published design curves to predict ammonia removal based on pilot and full-scale operating data. They plotted effluent concentration on the x-axis, and surface area required per pound of ammonia as nitrogen oxidized per day on the y-axis. Multiple curves were drawn to represent different temperature regimes (Figure 2). Designers simply must know the desired effluent concentration and wastewater temperature to use the curves. Using the desired effluent concentration and knowing the wastewater temperature, the plot can be traced to the surface area required per pound of ammonia as nitrogen oxidized per day. The anticipated influent ammonia concentration, design volumetric flow rate, and desired effluent ammonia concentration are used to find the weight of ammonia removed per day. This amount is multiplied by the value found from the design curves, and the total surface area needed in the trickling filter is then known. Total surface area required divided by the specific surface area of the plastic media gives the total volume of the trickling filter system.

Gujer and Boller (1986) developed an empirical design equation based on transport theory. Their model (Equations 1 & 2) was published in the EPA Manual for Nitrogen Control (US Environmental Protection Agency, 1993). Equation 1 or 2 can be solved for the depth of the trickling filter needed by assuming or estimating the operating parameters and model coefficients. The saturation parameter, maximum ammonia as nitrogen mass flux, and depth parameter can be assumed based on literature values or they may be found from evaluation of pilot study data.
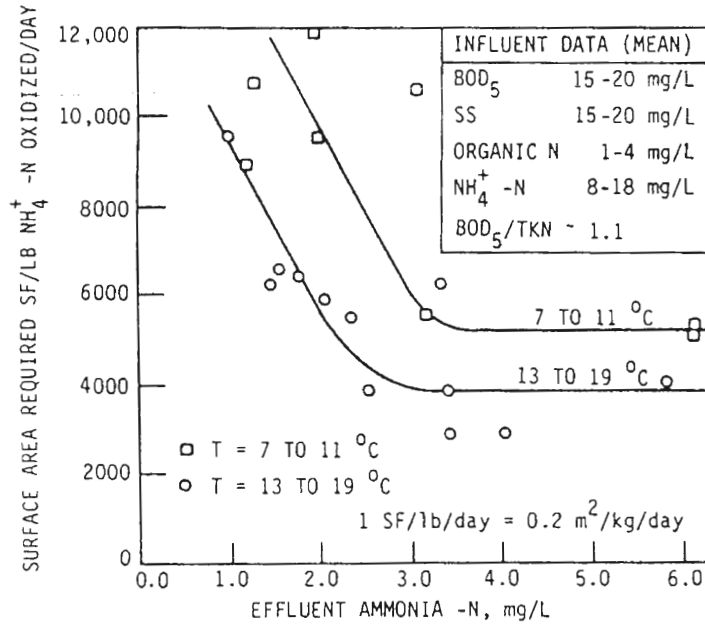
Figure 2a. EPA design curves for nitrifying trickling filters: Midland, Michigan data (Gullicks and Cleasby, 1986).
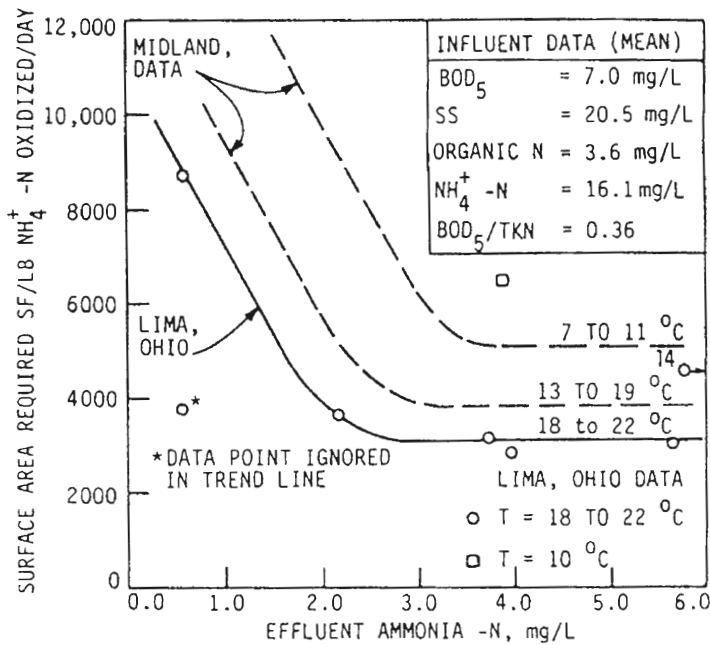
Figure 2b. EPA design curves for nitrifying trickling filters: Lima, Ohio data (Gullicks and Cleasby, 1986).

$$\frac{aj_{N,\max}}{kv_H}\left[1-e^{(-kz)}\right]=S_{N,i}-S_N+N\ln\left(\frac{S_{N,i}}{S_N}\right) \qquad \text{Equation 1}$$

$$\frac{zaj_{N,\max}}{v_H}=S_{N,i}-S_N+N\ln\left(\frac{S_{N,i}}{S_N}\right) \qquad \text{Equation 2}$$

a = specific surface area, m^2m^{-3}

$j_{N,\max}$ = maximum ammonia as nitrogen mass flux, $gm^{-2}day^{-1}$

k = empirical depth parameter, m^{-1}

N = saturation parameter, gm^{-3}

$S_{N,i}$ = Initial NH_3-N concentration, gNm^{-3}

S_N = NH_3 concentration, gNm^{-3}

v_H = Hydraulic load of trickling filter, $mday^{-1}$

z = depth, m

Logan et al. (1987) developed a model for organics removal based on transport processes in trickling filters. Logan later modified the model to solve for ammonia removal (Logan, 1993). Details about the plastic media are part of the program input into the program along with hydraulic loading, biofilm thickness, recycle fraction, ammonia diffusivities in water and biofilm, influent ammonia concentration, influent oxygen concentration, maximum growth rate, the half saturation constants for ammonia and oxygen, biofilm cell concentration, and cell yield values. Default values for the constants may be used if the actual values are not known. Output from the model includes the effluent ammonia

concentration, percentage ammonia removal, and the aerobic capacity of the final module (row of plastic media) in the trickling filter.

Rittman and McCarty also created a model (Rittman and McCarty, 2001) using a slightly different theoretical approach. Rittman used a pseudo-analytical solution of a set of differential equations derived from the transport of a chemical in the biofilm using a series of different assumptions. In one case, first-order kinetics are assumed and the mass flux of the substrate can be solved directly. In another case, the substrate concentration is assumed at the biofilm boundaries, and a simplified flux equation is offered.

Finally, a steady-state biofilm solution is given, and the steps to using the model are explained. The model requires six basic steps to find the values for the three dimensionless parameters. From the dimensionless variables, the mass flux of the system and the biofilm depth are computed. The drawback of Rittman's model is that the values for the biomass density, the diffusion coefficient in water, the diffusion coefficient in biofilm, the thickness of the effective diffusion layer, and the biofilm loss coefficient need to be estimated. Rittman and McCarty (2001) offer hints on how to estimate these parameters.

Purpose and Objectives

Parker has suggested (Parker, 1999) that six myths have been propagated throughout the environmental field without a hard scientific foundation to support them.

- Trickling filter processes are less reliable than activated sludge processes.
- Trickling filters are poor performers in cold weather.

- Trickling filters are more expensive.

- Motorized distributor control is always needed.

- Cross-flow media should not be used at total organic loadings exceeding 1.6 kg BOD_5/m^3.

- All media are created equal.

In the conclusion, Parker states, "…it is hoped that additional plant-scale research will be stimulated and that future technical publications and MOPs (Manual of Practice) will permit trickling filter technology to develop on the basis of science rather than mere opinion." (Parker, 2001).

The AWPCF Nitrifying Trickling Filter Project was proposed to the City of Ames, at their behest, to aid in determining the nitrifying, or ammonia removal, capabilities of their facility, and especially their NTFs. The project is essentially a follow-up to the work performed by Dr. Harvey Gullicks at Iowa State University during which he developed a method that aided RCM Associates in designing the current ammonia removal process. The AWPCF is ammonia underloaded, but city personnel anticipate reaching the design loading within the next several years and would like to have an assessment of the removal capabilities of their treatment processes at the design condition.

The City's desire to determine the AWPCF's performance capabilities behooves the requisite goal of determining the nitrification performance of all the trickling filters under design ammonia loading conditions. The request by the City of Ames for this project implied a determination of ammonia removal capabilities in the AWPCF. Design loading conditions are approximately 1.5 to 2 times their current ammonia loading. The AWPCF anticipates a

gradual increase in ammonia loading, and the operators need to be assured that their processes will be capable of performing at design conditions. Additionally, it would be useful for the AWPCF staff to know how to manipulate operating variables in order to obtain peak performance.

The more fundamental goal of determining the effects of operating conditions, given the design variables, on trickling filter nitrification performance should be solved to assist the AWPCF personnel in finding the performance capabilities of the trickling filters. Gullicks hypothesized that four primary operating variables influence ammonia removal in trickling filters: ammonia influent concentration, hydraulic loading, recirculation, and temperature. The effects of these variables on ammonia removal were investigated in this study.

Hypotheses

A number of preliminary observations were made on the AWPCF's overall nitrifying capabilities, and the TFs and NTFs nitrifying capabilities. The facility is currently underloaded with respect to the ammonia and CBOD load. The facility's design loading for ammonia is 1,970 lbs-N/day at a CBOD loading of 12,430 lbs/day projected as the average annual load for the year 2010. The current average ammonia load is 1080 lbs-N/day based on operating data from January 1999 to February 2001.

The NTFs were designed in accordance with curves developed by Gullicks (1987). The curves developed by Gullicks were based on pilot and full scale data. The pilot project was performed at the former Ames Water Pollution Control Plant, and the data are specific for the Ames' wastewater treatment system.

Based on operating data, the TFs are removing roughly 60% of the ammonia load or greater. Consequently, the current flow scheme allows ammonia to be consumed before reaching the NTFs. The TFs were designed to remove CBOD, but are performing the function of the NTFs. Significant ammonia removal occurs despite influent CBOD concentrations of 100 to 200 mg/L for the TFs.

Hypotheses have been developed based on the preliminary observations. Noting the nitrifying capabilities of the TFs, it is hypothesized that CBOD concentration has little or no effect on the ammonia removal rate in the TFs at the AWPCF at current loading conditions. Gullicks' studies were performed to determine nitrifying capabilities of Ames' trickling filters, and it is hypothesized that the AWPCF trickling filters remove ammonia as predicted by Gullicks' (1989) design curves. More specifically, nitrification is dependent on a combination of factors including hydraulic load, ammonia influent concentration, recirculation, and temperature. The Gujer and Boller (1986) model employs these key operating variables, based on theoretical concepts, and can be calibrated to predict ammonia removal in the TFs and NTFs of the AWPCF.

CHAPTER 2. LITERATURE REVIEW

Ames Water Pollution Control Facility Design Curve Development

As previously noted, the work presented in this thesis is a follow-up study to the research conducted by Gullicks. Gullicks began the development of his design curves by analyzing the EPA's design curves (Gullicks and Cleasby, 1986). He found that the EPA's design curves were bereft of important operating variables and poorly explained the data used to develop the curves. Gullicks proposed four operating variables to be vital to nitrifier performance. Temperature, ammonia influent concentration, recycle rate, and hydraulic loading were predicted to have the greatest effect on ammonia removal. The data used in the EPA design curves were reorganized into two temperature regimes: temperatures between 10 and 14 degrees Celsius, and temperatures greater than 14 degrees Celsius. Ammonia removal was then plotted against the applied hydraulic load and influent ammonia concentration including recirculation.

The next stage of Gullicks' study was the development and analysis of a pilot scale nitrifying trickling filter (Gullicks and Cleasby, 1990a). A nitrifying trickling filter was built measuring 4.88m in height with a 0.61m by 0.61m cross-section (Gullicks and Cleasby, 1990b). The 60° cross-flow media had a specific surface area of 138 m^2/m^3. Ames' WPCF final clarifier effluent was fed into the trickling filter to develop a nitrifying population. Due to concerns that excessive organic loading would allow heterotrophs to outcompete the nitrifiers, a pretreatment trickling filter, identical to the pilot NTF, was constructed with a clarifier.

Samples were taken from the nitrifying trickling filter at 1.22m intervals, and analyzed for ammonia, nitrate, alkalinity, COD, TKN, and solids concentrations. The specific ammonia removal rates were determined from the data acquired. The removal rates were adjusted to a 10°C standard by multiplying the observed removal rate by the diffusion constant for oxygen in water at 10°C, and dividing by the diffusion constant for oxygen in water at the wastewater temperature measured on site during acquisition of the samples. A site specific set of design curves was then developed based on the data acquired (Figure 3).

The design curves are simple to use, but the clearly stated assumptions should be observed. The design curves are intended for development of a nitrifying trickling filter built to remove ammonia of a wastewater with low CBOD and TSS concentrations. The media should be 6 to 6.5 meters in depth with a specific surface area of 89 to 98 m^2/m^3. Additionally, the design curves assume a conservative wastewater temperature of 10°C.

To use Gullicks' curves, begin with an estimate of the influent ammonia concentration including recirculation, determine a desired hydraulic loading rate (cross-sectional area given a design flow rate with recycle), and interpolate until a trickling filter has been designed that meets the curve assumptions of specific surface area and tower height. The desired daily ammonia removal rate is found based on the flow rate, the influent ammonia concentrations, and the required effluent ammonia concentration. The specific ammonia removal rate is found by intersecting the influent ammonia concentration and hydraulic loading on the design curves.
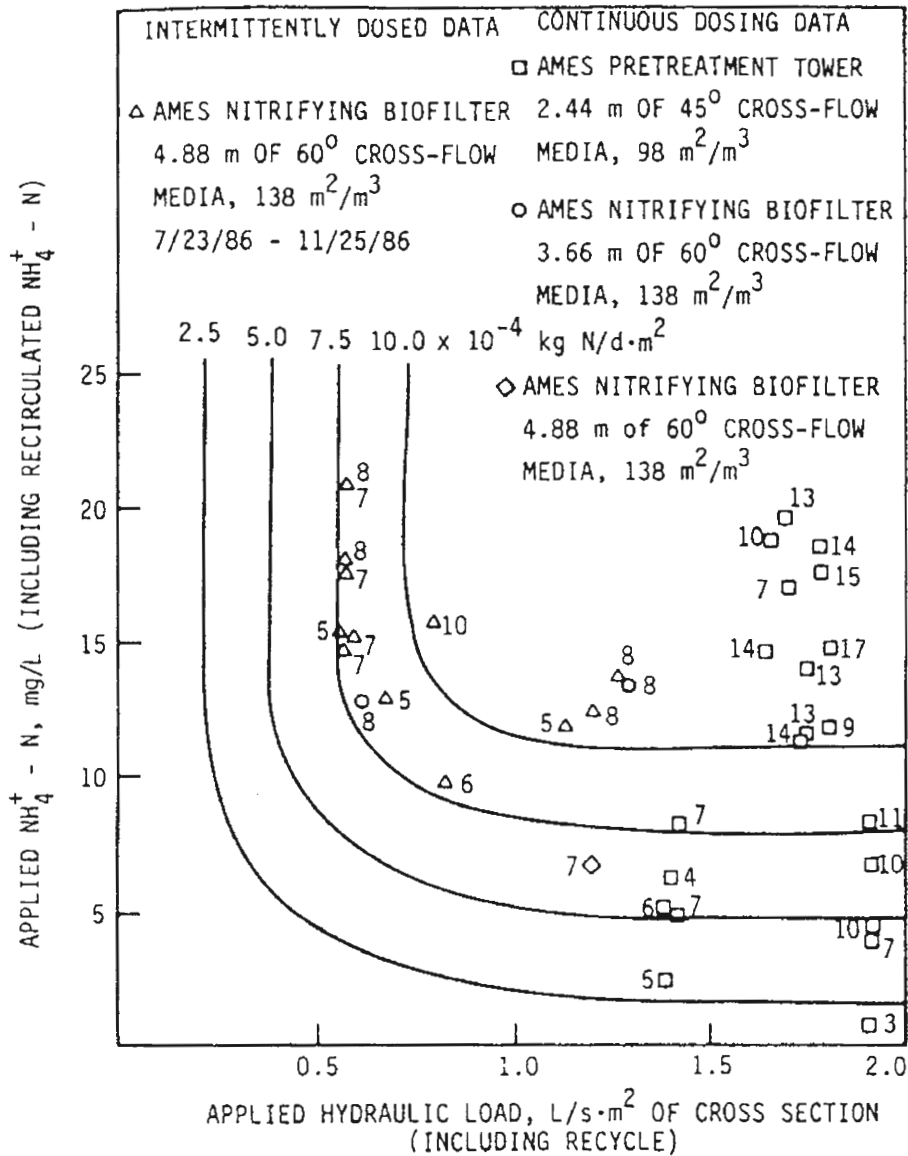
Figure 3. Gullicks design curve based on pilot scale study, adjusted to 10°C basis (Gullicks, 1987).

The daily removal rate divided by the specific removal rate gives the total surface area required to achieve the necessary removal. The total surface area can then be divided by the specific surface area of the media to give the total media volume. The total volume is then divided by the cross-sectional area assumed for hydraulic loading to give the depth of

the plastic media. This depth should be in the range of 6 to 6.5 meters as suggested by the assumptions. If not, the cross-sectional area, recirculation rate, or other parameters should be adjusted and the problem reiterated.

Gullicks made many important conclusions based on his pilot study (Gullicks and Cleasby, 1990b). For instance, the dissolved oxygen concentration is critical to the performance of nitrifiers in an oxygen flux limited situation. Any reductions in dissolved oxygen concentration can have dramatic negative effects on nitrifier performance.

The requirement of a low soluble COD concentration may be less critical than previously assumed. Gullicks and Cleasby (1990b) noted, "Wanner and Gujer predicted that nitrifiers would be completely displaced from the biofilm at sustained, bulk-liquid soluble COD concentrations greater than 27 mg/L." Gullicks observed that nitrification occurred at sustained soluble COD concentrations of 60-66 mg/L. These high total COD concentrations suggest soluble COD greater than the 27 mg/L value of Wanner and Gujer. Ammonia removal has been observed at CBOD concentrations in excess of 100 mg/L in the TFs at the current facility.

Gullicks achieved significant progress in his research of nitrifying trickling filters. At the same time, he recognized the need for continued research to optimize and increase confidence in performance. Gullicks' research has implications for this study. His design curves were useful for predicting ammonia effluent concentrations in the AWPCF. The observed nitrification at high COD concentrations suggests that the TFs at the AWPCF may be expected to remove ammonia.

Nitrifying Trickling Filter Empirical Analysis

Okey and Albertson (Okey and Albertson, 1987) analyzed nitrifying trickling filter data and compared it to modern theory while reasoning the most plausible explanation for observed results. Okey and Albertson studied data from a number of pilot scale facilities and one full-scale facility. Their work studied nitrification rates in a full-scale nitrifying trickling filter.

Most studies have observed a change in rate with respect to NH_3-N from zero-order in the upper depths of a trickling filter to first order in the lower depths of a trickling filter. Okey and Albertson concurred that oxygen diffusion was the key limiting factor for zero-order with respect to NH_3-N removal rates, and NH_3 was the key limiting factor for first-order with respect to NH_3-N removal rates.

Okey and Albertson hypothesized that temperature effects on metabolism are balanced by increased oxygen diffusivity. They reasoned that if temperature is accounted for in a model, it should be in terms of diffusivity. They claimed that they could attribute no effects on ammonia removal to hydraulic loading. Based on their findings, they developed a two part model in which ammonia removal is dependent on the sum of both a term accounting for zero-order removal and a term describing first-order removal. A plot is presented in their paper showing effluent ammonia concentration as a function of ammonia loading rate and percentage saturation of dissolved oxygen concentration. Their curves show that dissolved oxygen concentration is an important factor in ammonia removal.

Their work agrees with the findings of Gullicks (1987) on nearly every point. Gullicks believed, however, that hydraulic loading was an important factor in nitrifying

trickling filter design. Okey and Albertson allude to the effects of hydraulic loading as being small when compared to other factors like oxygen supply and ammonia loading.

Theoretical Model Approximation

Perhaps the best known and most widely accepted modern design approach for nitrifying trickling filters was developed by Gujer and Boller (Gujer and Boller, 1986). They began by performing a differential mass balance for a dissolved species, in this case ammonia, across the biofilm. The mass balance is simplified and solved by assuming steady state conditions, Fick's first law for diffusion, and Monod microbial kinetics. A series of diffusion equations is generated for balancing diffusion of the electron donor and electron acceptor. Oxygen or ammonia diffusion limitations are then recognized and solved in terms of an overall mass transfer coefficient. Experimental results validated their equations.

Unfortunately, their equations could not be integrated over the depth of the reactor analytically. They, therefore, developed an approximation (Equation 3) of their theoretical equations. Equation 3 was modified (Equation 4) for the purposes of tertiary nitrifying trickling filter design. Next, a differential mass balance across the depth of the biofilm was performed. Steady state conditions were assumed, and Equation 4 was substituted as the overall flux into the biofilm. The model was integrated and the result was Equations 1 and 2 presented in the introduction.

$$j_N(s,T) = j_N(s = \infty, T = 10°C) \exp[0.044(T-10)] \frac{s_{N,b}}{N + s_{N,b}}$$ Equation 3

$j_N(s_{N,b},T)$ = mass flux of ammonia due to molecular diffusion at a biofilm depth s and a temperature T, $gm^{-2}day^{-1}$.

$s_{N,b}$ = ammonia concentration at a biofilm depth b, gm^{-3}.

N = saturation parameter for substrate limitation, gm^{-3}.

$$j_N(z,T) = \exp(-kz) j_{N,max}$$ Equation 4

$j_N(z,T)$ = mass flux of ammonia at a depth z, and a temperature, T, $gm^{-2}day^{-1}$

The values for k, $j_{N,max}$, and N can be assumed to be the values given by Gujer and Boller in their articles, or can be determined from a pilot scale study or a calibration based on operational data. Data with ammonia concentrations at different depths of the trickling filter will improve estimation of the constants. With the calibrated constants, the influent concentration can now be substituted into the equation, and the design and operational conditions input to find the effluent concentration. Alternatively, the desired effluent concentration can be input and design and operational conditions can be solved.

It is notable that the Gujer and Boller design model has the same inputs (i.e., influent concentration, hydraulic loading, and temperature) as Gullicks' model. The curves generated by theoretical concepts in Gujer and Boller (1986) show bulk ammonium concentration in wastewater versus ammonium flux with different curves representing different temperatures

(Figure 4). Gujer and Boller's curves apparently isolate for one hydraulic loading. Gullicks' model isolates the temperature in order to observe different hydraulic loadings. Gujer and Boller's model may be useful for predicting ammonia effluent concentrations for the AWPCF trickling filters if it can be calibrated.
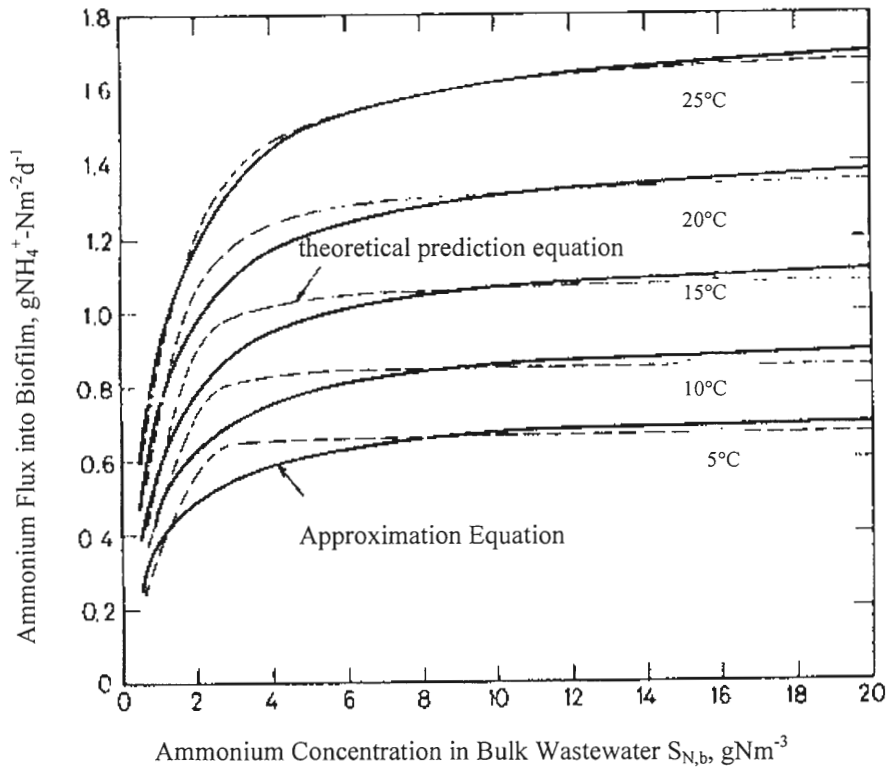
Figure 4. Ammonia flux curves generated by the Gujer and Boller approximation compared to theoretical flux curves (Gujer and Boller, 1986).

Theoretical Model Solved with Numerical Approximation

Logan (1987) developed a model by analyzing a differential control volume for oxygen in the bulk liquid phase (Equation 5), and inside the biofilm (Figure 5). Boundary conditions are set by determining the dissolved oxygen concentrations entering the trickling filter media, at the air-water interface, and at the liquid-biofilm interface. The dissolved

oxygen concentration at the liquid-biofilm interface is dependent on the substrate uptake in the biofilm.

$$\mu_{max} \left[1 - \left(\frac{x}{\delta} \right)^2 \right] \frac{\partial c_{Ow}}{\partial z} = D_{Ow} \frac{\partial^2 c_{Ow}}{\partial x^2}$$

Equation 5

μ_{max} = maximum velocity of wastewater on the edge of the liquid flow surface

x = depth into liquid flow

δ = total liquid flow depth

c_{Ow} = concentration of oxygen in the water

z = vertical distance

D_{Ow} = diffusion of oxygen in water

x = horizontal distance

.

Logan solved the model with a numerical approximation. A FORTRAN algorithm was developed to simplify solving the model. Detailed information about the media is needed because Logan assumes that the wastewater is completely mixed at each of the nodes in the plastic media, thereby refreshing the supply of dissolved oxygen to the saturation point, which is dependent on the temperature, altitude, and dissolved solids level, of the wastewater.

Logan's model and program assume oxygen flux limiting conditions. Oxygen flux limiting conditions only exist when the bulk ammonia concentration is 3 to 5 mg-N/L. For ammonia concentrations below this level a different model must be used.
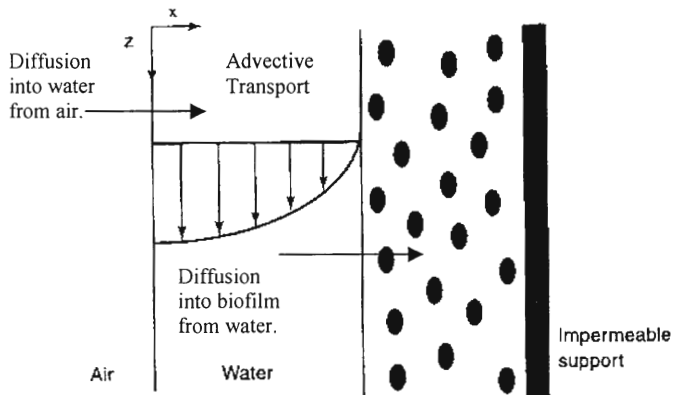
Figure 5a. Logan's control volumes for analysis of the transport equation over a differential element in the bulk liquid in a trickling filter (Logan, 1999).
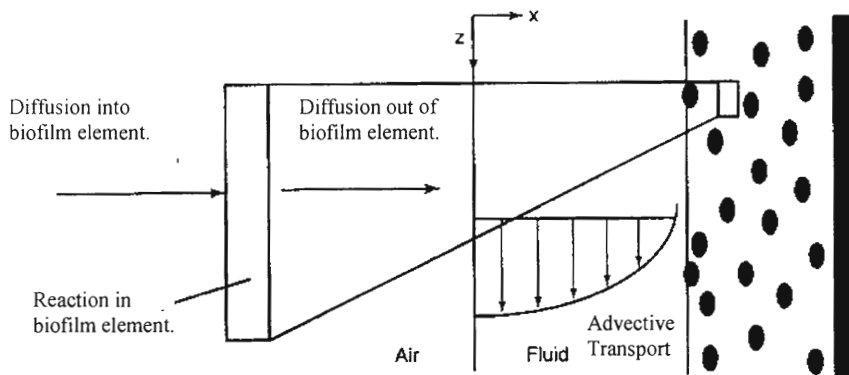
Figure 5b. Logan's control volumes for analysis of the transport equation over a differential element in the biofilm in a trickling filter (Logan, 1999).

Theoretical Model Solved Pseudo-Analytically

Rittman and McCarty also looked to transport theory to solve the riddle of substrate uptake in biofilms (Rittman and McCarty, 2001). Rittman and McCarty assume an idealized biofilm type where the density is uniform and the biofilm thickness is constant. The key difference between Rittman's model and Logan's model is that Rittman isolates transport of chemicals in a biofilm element rather than in the liquid.

The solution can be found analytically if both the substrate concentration at the biofilm-liquid interface is known and if the concentration is known where the biofilm is attached to the media. A solution is thus known for deep biofilms since the substrate is completely consumed in a deep biofilm. Rittman and McCarty pseudo-analytically solved the transport problem by numerically solving for a value that adjusts biofilms that are not deep.

$$J = f \, J_{deep} \hspace{4cm} \text{Equation 6}$$

J = actual steady-state flux

f = ratio adjusting to a biofilm that is not deep (value between 0 and 1)

J_{deep} = flux into a deep biofilm

Measuring Nitrification of Activated Sludge with Respirometry

Riefler et al. (1998) used respirometry to characterize kinetic coefficients for nitrification in a suspended culture. They discovered that the data received from respirometric testing of nitrification did not fit a Monod type substrate consumption curve as well as the curve for removal of compounds by heterotrophic bacteria. Analysis of data for nitrification in a respirometric test using heterotrophic kinetic coefficients may be incorrect.

As a result, the terms were adjusted for substrate utilization using an electron balance to account for the nitrogen used for energy to generate a carbon source, for energy used for maintenance, and as a nitrogen source for the cell (Figure 6). The new model isolates only the nitrogen oxidized. The yield is expressed as nitrifier biomass generated per ammonia as nitrogen oxidized in units of milligrams Nitrogenous Oxygen Demand (NOD) (Equation 7). The new yield expression is then substituted into the Monod based equations for substrate consumption, oxygen uptake, and biomass growth.

The solids contact process at AWPCF may be removing a significant amount of ammonia. Respirometry can be used to characterize its ammonia removal capabilities. The method of analysis developed by Riefler et al. (1998) was applied in this study.
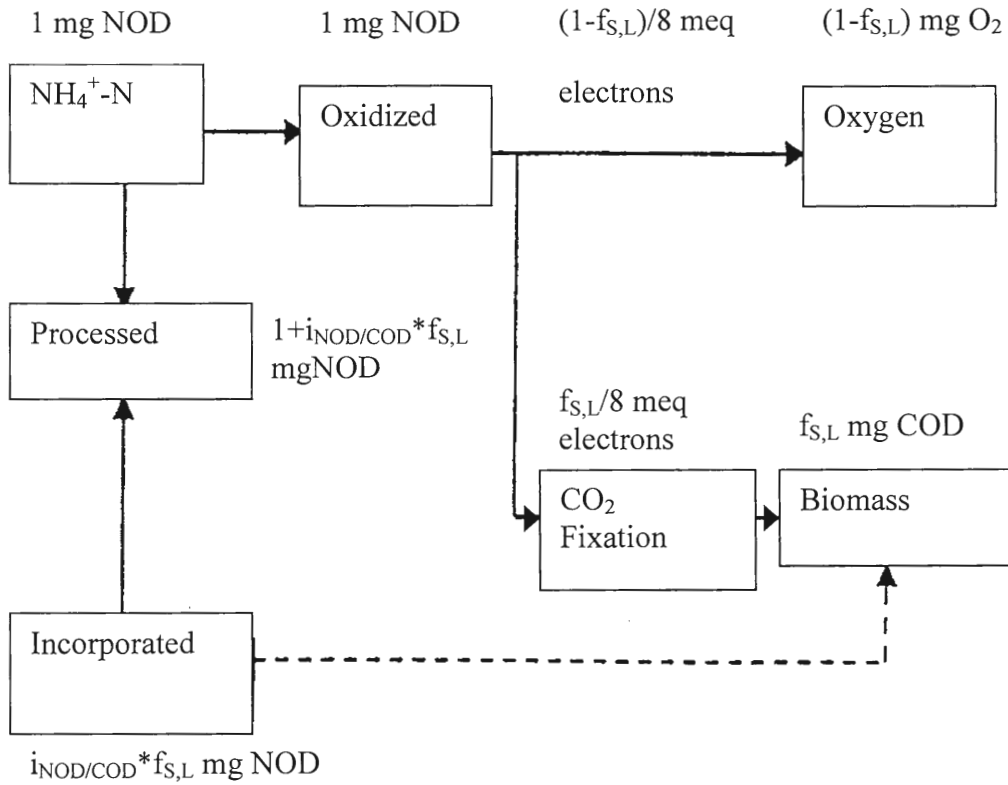
Figure 6. Nitrogen flow diagram for nitrification process (Riefler et al., 1998).

$$f_{S,L} = \frac{\left(S_{nho} - OU_{nh,f}\right)}{\left(S_{nho} + \left(0.4 OU_{ns,f}\right)\right)}$$
Equation 7

$f_{S,L}$ = lumped biomass yield coefficient (mg X_{nh}-NOD produced / mgNH$_4^+$-NOD oxidized)

S_{nho} = NH$_4^+$-N oxidized (mg NOD / L)

$OU_{nh,f}$ = Oxygen uptake accompanying oxidation of NH$_4^+$-N to NO$_3^-$ (mg O$_2$ / L)

X_{nh} = total nitrifying biomass concentration (mg COD / L)

CHAPTER 3. MATERIALS AND METHODS

Analysis of Operating Data

A cornucopia of insight lies in a decade of operating data from the AWPCF. The plant has been in operation since 1989, and has kept records on CBOD, solids, ammonia, temperature, and pH before and after processes throughout the plant.

Operating data from August 1998 to June 2000, and throughout the study have been obtained for examination. Temperature and pH probes remain immersed in the raw influent stream and in an effluent side sampling stream to continuously monitor the wastewater. Ammonia, CBOD, and solids data are procured from 24 hour, flow-weighted composite samples taken at key locations throughout the plant (Figure 7). The samplers are housed in shelters to protect them from the weather, and the samples are refrigerated at 4°C before being transported directly to the lab for immediate analysis. The lab follows standard methods (APHA et al., 1995) in all their analyses. Ammonia is measured using an auto analyzer based on spectrophotometry. The detection limit is 0.5 mgN/L.

The operating data are useful in many ways. Simple observations of the data were used to assess ammonia concentrations at locations throughout the plant, ascertain ammonia removal levels for different plant processes, understand plant flows and recirculation for the trickling filters, to acquire plant yield information, and to establish general seasonal trends. Closer examination of the operating data was used to reveal the accuracy of Gullicks' (1987) design curves, to show the effect of CBOD on ammonia removal in the TFs, and to adjust ammonia removal data to a 10°C basis.
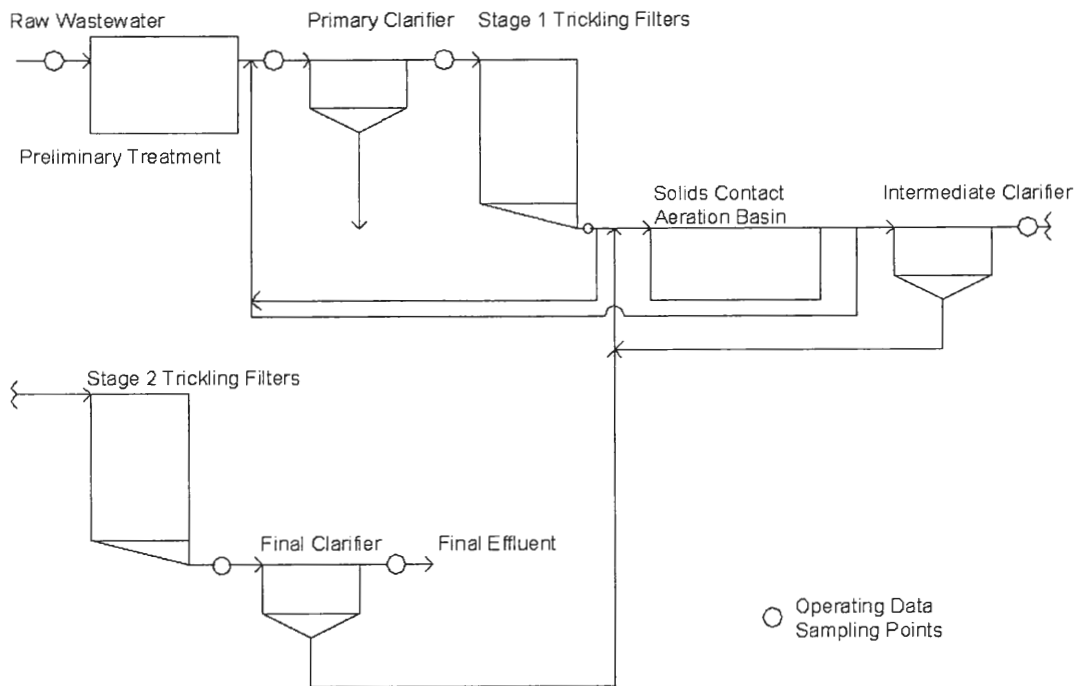
Figure 7. Operating data sample locations.

Experimental Plan

Researchers examining nitrifying trickling filters have introduced a number of theoretical and empirical models. Gullicks (1987) suggested four variables: wastewater temperature, hydraulic loading, ammonia influent concentration, and recycle rate, as being important to the nitrifying rate observed in trickling filters. Other models concur, implicitly or explicitly, with the use of these four inputs. The Gujer and Boller (1986) model utilizes the same inputs to determine ammonia removal (Equations 1 & 2). More complicated theoretical models, Logan (1987) and Rittman and McCarty (2001), closely examine transport limitations across the wastewater and biofilm. While the theoretical models are complex, the fundamental components are advection and diffusion. Advection is dependent

on the hydraulic loading rate and the substrate concentrations. Diffusion into the biofilm is dependent on temperature and the substrate concentrations.

Nitrification at the AWPCF is reportedly oxygen flux limited when the bulk wastewater ammonia concentration is above approximately 4 mgN/L (Gullicks and Cleasby, 1990a). Models can account for this by explaining the ammonia removal rate in terms of the oxygen flux rate as performed by Gujer and Boller (1986). The research performed in this study exclusively examines the ammonia removal rate as a response to influent ammonia concentration, hydraulic loading rate, recirculation, and temperature. Recirculation can be accounted for implicitly by obtaining adjusted influent ammonia concentrations and hydraulic loading rates.

The concentration of soluble COD purportedly also affects the rate of nitrification in trickling filters (Wanner and Gujer, 1984). Gullicks and Cleasby (1990a) however found significant nitrogen removal rates at soluble COD concentrations of 49 to 90 mg/L in the pretreatment trickling filter of a pilot study. The effect of CBOD on nitrification in the TFs is examined in this study based on operating data from January 1989 through December 2001. Ammonia removal rate was standardized for temperature, influent ammonia concentration, and hydraulic loading and then compared at different influent CBOD concentrations.

The adjustments to influent ammonia concentration and hydraulic loading were made by dividing by the actual influent ammonia concentration and hydraulic loading, and multiplying by the average values for each over the data period. Chemical oxygen demand and soluble COD effects were estimated using a COD to CBOD ratio and solids data found from plant composite samples over a four week period. If no statistically significant negative

linear relationship is found between ammonia removal rate and influent CBOD concentration, then the relationship is either nonlinear, CBOD affects ammonia removal by a constant factor, or CBOD does not affect ammonia removal in the TFs. If CBOD concentration does not affect ammonia removal, or affects it by a constant factor, then removal rate dependence on other factors can be examined separately from or without regard to CBOD concentration. The nitrification rates occurring in the TFs are significant. Data from the TFs add valuable insight into the nitrifying capabilities of the AWPCF and has been included in the experimental study of the NTFs.

Ammonia removal in trickling filters can be studied in detail with sampling ports as suggested and requested in the initial proposal for this project. The trickling filter sampling port installation was abandoned due to costs and concerns over structural stability of the concrete panels that make up the walls of the trickling filters. This was a setback to the study. They were important to gaining an understanding of ammonia removal within the trickling filters. Calibration of the model developed by Gujer and Boller (Gujer and Boller, 1986), using a numerical solution to the differential equation of change in concentration with depth, was dependent on obtaining sampling port data. The AWPCF wisely would not sacrifice the reliability of their system for easy sampling.

In lieu of not having sampling ports, a different experimental approach was developed. The flow scheme at the AWPCF was changed to increase the ammonia loading on the NTFs. The solids contact process was shifted in the scheme so that it was after the NTFs. Ammonia loading on the NTFs increased from less than 70 lbs/day to between 100 and 150 lbs/day. The desired result was achieved, but the ammonia load was still less than 10% of the design load of 1,970 lbs/day.

The next step was to adjust the sluice gates at the splitter box to increase the flow to one of the trickling filters and reduce the flow to the other, thereby adjusting the hydraulic loading. A pan test was used to determine the flow distribution between the trickling filters. The flow rate to the trickling filters remains constant due to pumping, but the recirculation ratio changes depending on the influent wastewater flow rate

Grab samples were then taken three to five times per week from the influent and effluent of the trickling filters. Influent samples were taken directly from the top of the trickling filter media by placing a two liter beaker on the media to capture the wastewater after it flows off the arms. 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 hours, or preserved and tested within one week as suggested by Standard Methods (APHA et al., 1995). A number of samples have also been tested for nitrates to confirm nitrification and to perform a nitrogen balance on the system.

The low ammonia concentrations in the influent to the NTFs do not allow an observation of maximum removal capabilities. It may be possible, however, to extrapolate the removal capabilities at higher loadings based on current conditions. The extrapolation will not be as reliable as a direct observation.

The variables of interest, therefore, are the operating variables, and ammonia flux is the single response variable. The hydraulic loading is the only operating variable that was intentionally manipulated in this study. Other operating variables were merely observed.

The observed operating variables are the influent ammonia concentration and the recirculation rate.

Ammonia removal data obtained from operating data and from the current study has been compared directly to Gullicks' (1987) curves. The data obtained have been plotted as ammonia flux curves versus ammonia influent concentration and hydraulic loading rate as in Figure 3. Gullicks' curves were then reproduced and superimposed over the new data points. General comparisons have been performed, but no statistical significance has been drawn directly since the curves were plotted by hand. Gullicks' curves are a two dimensional representation of a three dimensional function. Therefore, as an alternative, the curves have been approximated with a three dimensional equation that can be compared with the data.

The Gujer and Boller (1986) model (Equation 2) has been algebraically manipulated to allow interpretation by means of the same variables used in Gullicks model (Figure 8). The modified equation was written in terms of influent ammonia concentration, hydraulic loading, observed removal rate and two constants, maximum ammonia removal rate and the saturation parameter for substrate limitation (Equation 8). The equation was solved explicitly for influent ammonia concentration.

The data were used to calibrate Gujer and Boller's model by calculating the influent ammonia concentrations with Equation 8 given the operating conditions and comparing the calculated influent ammonia concentration to the actual influent ammonia concentration. The sum of the squared difference between the two influent ammonia concentrations was minimized using the Excel 2002© solver function with the calibrated constants input into the adjustable cells, or a non-linear analysis performed in the statistical software JMP©.
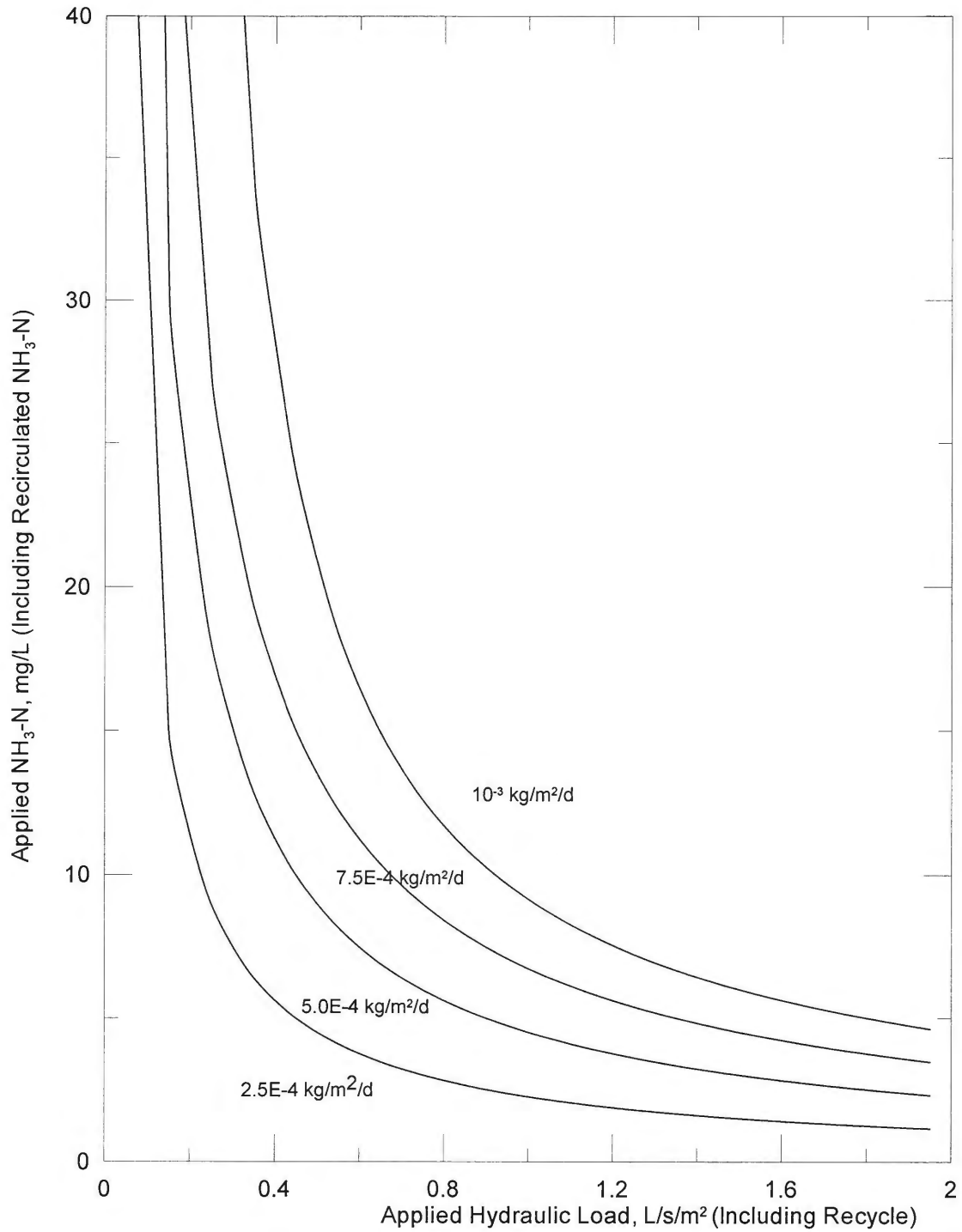
Figure 8. Gujer and Boller's model plotted as Gullicks' type curves with $j_{n,max}$ = 1.02E-3 kg/m^2/day and N = 0.32 kg/m^3.

$$S_{N,i} = \frac{azj_n}{v_H \left[1 - \exp\left(\frac{(j_n - j_{N,max})az}{Nv_H} \right) \right]}$$

Equation 8

j_n = actual ammonia flux

Sample Analysis

Samples were analyzed for a number of different compounds and characteristics. The pH was determined in a limited number of samples to verify that the pH was optimal, 6.8-7.3, for activity of nitrifying bacteria. Biochemical oxygen demand and COD were measured in samples to find the level of biodegradable organics in the wastewater throughout the plant. Previous studies (Wanner and Gujer, 1984) have indicated that at high levels of soluble COD, nitrification will not occur in a trickling filter due to competition with heterotrophs. Ammonia and nitrates were measured to follow nitrification in the trickling filters and other locations throughout the facility.

The pH of the samples was analyzed by Method 4500-H^+ B of Standard Methods (APHA et al., 1995) using an Orion gel filled pH electrode model number 91-05 with a standard reference electrode. The pH meter used was Cole Palmer Model 05669-20. The probe and meter were calibrated before each series of readings. A series is constituted by a group of samples measured together immediately after returning from the wastewater treatment plant.

Total CBOD was analyzed on plant composite samples in accordance to Method 5210 of Standard Methods (APHA et al., 1995). Two dilutions of each sample were measured.

Two replicates of each dilution were performed. The CBOD values obtained were then averaged. The value was neglected if the final dissolved oxygen concentration was below 1.0 mg/L or if the change in dissolved oxygen concentration was less than 0.5 mg/L.

Total COD was analyzed on plant composite samples in accordance to Method 5220 of Standard Methods (APHA et al., 1995). Raw influent and primary influent samples were diluted 20 times. One replicate was performed of each sample and the values were averaged. Estimation of soluble COD was made based on subtracting an estimated solids COD, using 1.42 mg COD per mg VSS, from measured and estimated total COD.

Ammonia concentrations were measured in samples using an Orion ammonia electrode probe Model 95-12 in accordance to Method 4500-NH_3 D of Standard Methods (APHA et al., 1995). The probe was attached to Corning Incorporated pH/Ion Analyzer Model 350. The internal filling solution purchased from ThermOrion was diluted ten times to enhance measurement at low ammonia concentrations as instructed by the manual. The probe was calibrated before each use by measuring four standard solutions: 0.1, 1.0, 10, and 100 mgNH_3-N/L, and a standard curve was developed. The detection limit noted by the manual for the probe is 0.07 mgNH_3-N/L. The range for sample concentrations was generally between 0.08 and 30 mgNH_3-N/L.

Nitrates were measured using ion chromatography (IC) on Dionex equipment. The equipment consisted of a CD20 conductivity conductor, a GP40 gradient pump, an AS40 auto sampler, a P/N 53946 supressor, and a P/N 5070 column. Data were recorded onto a PC with the Dionex Peaknet Chemo workstation. The elluent consisted of 0.1 mM sodium bicarbonate and 3.5 mM disodium carbonate at a flow rate of 2.0 mL per minute. The standard solution used contained 10 mgNO_3^-N/L. The detection limit was observed to be

approximately 1.0 $mgNO_3^-N/L$ found by testing a series of known standards. The range for sample concentrations was generally zero to 40 $mgNO_3^-N/L$.

Pan tests were performed using either four gallon buckets or custom cut containers. The custom cut containers were the bottom 20 to 30 inches of two 55-gallon drums. They were cut using a circular saw. Two to four containers or buckets were placed on the trickling filter media. The arms completed one rotation, and the containers were then removed and the volume of water was measured. The rotational speed of the arms was timed simultaneously. The fraction of flow to a pair of trickling filters was then approximated by the fraction of volume per time flowing into the containers.

An extant respirometry test was performed in accordance with the procedure suggested by Riefler et al. (1998) to determine the kinetic characteristics of the nitrifying bacteria in the solids contact process. The extant respirometry test was performed in four respirometers using mixed liquor from the AWPCF aeration basin. Injections of ammonium chloride were performed, and the data were collected on a PC using the program Labtech Notebook (Adept Scientific, Bethesda, MD). The data were analyzed by solving for the kinetic constants for full nitrification in Riefler et al. (1998). A sum of squares regression for the numerical approximation of the kinetics model was performed in Excel 2002©.

CHAPTER 4. RESULTS

Operating Data

The operating data contain a wealth of knowledge hidden in sample observations. The data were useful to determine general and specific characteristics at the AWPCF. Plant yield values were found by examining the volatile suspended solids (VSS) and CBOD concentrations from raw influent, final effluent, and primary clarifier sampling stations. Ammonia removal throughout the AWPCF was profiled to observe which processes were removing ammonia, and to quantify that removal.

The CBOD removing TFs were examined in great detail. The TFs remove a significant amount of ammonia. Ammonia removal was compared to an estimated soluble COD influent concentration in the TFs to better understand the interaction between the two. The TFs operating conditions and ammonia removal were compared to Gullicks' design curves (1987). Operating data showed that the NTFs were removing only a small percentage of the overall plant ammonia load (Figure 9). The ammonia concentration difference between the intermediate clarifier effluent and NTF effluent is what has been removed in the NTFs. The ammonia effluent concentration for the NTFs rarely exceeds the detection limit for the AWPCF lab analysis.

Microorganisms grow and reproduce as a result of their consumption of organic and inorganic matter in the wastewater. A useful indicator of the health and characteristics of a population is the yield at the wastewater treatment plant. An average plant yield for the AWPCF was calculated to be 0.204 mgVSS/mgCBOD based on plant operating data from

October 2000 to December 2001 (Table 2). The AWPCF is a trickling filter plant and, therefore, the microorganisms will tend to remain in the system for extended periods of time and decay leading to a lower yield value than at a typical activated sludge plant. Nitrifier yield was neglected in this calculation, and all solids generated in the plant were assumed to come from heterotrophic growth. Nitrifier yield will likely be small compared to the heterotrophic yield. For example, if the true nitrifier yield is 0.15 mg $VSS/mgNH_4^+$-N, then at a typical AWPCF ammonia removal of 1000 lbsN per day, the biomass generated as a result of autotrophic growth will be only 150 lbs VSS. This is roughly 5% of the VSS being generated by biomass growth.
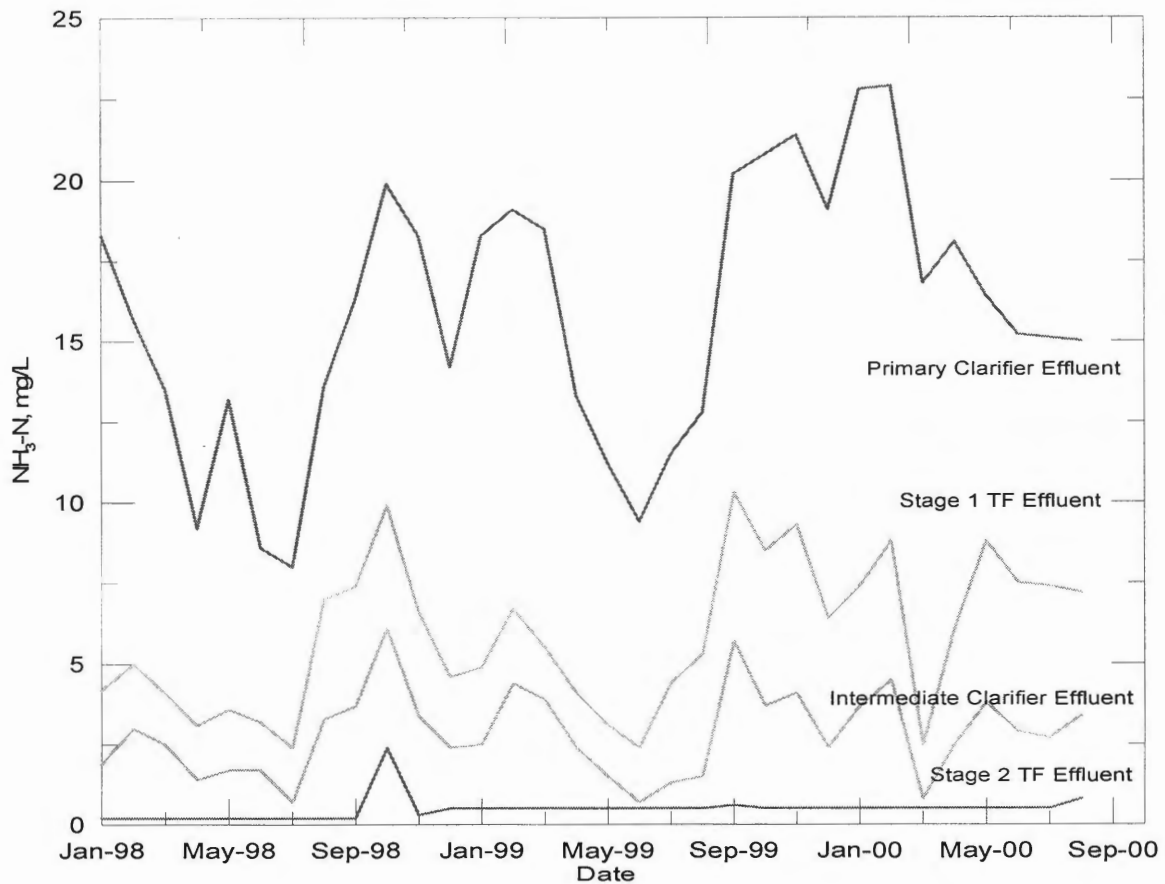
Figure 9. Ammonia concentrations through AWPCF over a 2 ½ year period.

The effect of CBOD loading on ammonia removal was examined in the TFs. Traditionally, it has been claimed that nitrification will not occur in trickling filters if the wastewater has a high soluble COD concentration. Wanner and Gujer (Wanner and Gujer, 1984) suggested that at sustained bulk filterable COD concentrations greater than 27 mg/L, nitrification will not occur because nitrifiers would be completely displaced from the biofilm. The data from the AWPCF contradict this hypothesis and suggest that nitrifiers and heterotrophs coexist in a single trickling filter at much higher COD concentrations. Based on composite samples, the COD/CBOD ratio for the first stage TFs influent was found to average 2.2. Using this information, an estimate of COD concentration was made. Solids were then assumed to have a COD value of 1.42 gCOD/gVSS and the COD value of the solids was then subtracted from the COD estimate to give an estimate of soluble COD.

The influent soluble COD concentrations and ammonia removal percentage for the first stage TFs were then compared (Figure 10) and statistically analyzed. Ammonia removal does not have a significant negative linear relationship with the estimated influent soluble COD concentrations for the TFs. In fact, the data reveal a weak positive linear relationship. An increase in ammonia removal percentage was found to be significant at an alpha value of 0.05 when compared with soluble COD using a statistical F-test.

Table 2. AWPCF monthly yields.

Month	Yield (mgVSS/mgCBOD)
Oct-00	0.35
Nov-00	0.29
Dec-00	0.21
Jan-01	0.17
Feb-01	0.31
Mar-01	0.12
Apr-01	0.11
May-01	0.20
Jun-01	0.21
Jul-01	0.22
Aug-01	0.12
Sep-01	0.08
Oct-01	0.29
Nov-01	0.19
Dec-01	0.19
Average	0.20±.08

The ammonia removal observed in the TFs, based on the operating data, was compared to Gullicks' curves (Figure 11). The AWPCF TFs operate in a limited range of hydraulic loadings. Most of the data points are at 0.4 L/s/m^2. The data points in the range of hydraulic loadings between 0.4 to 0.8 L/s/m^2 roughly follow the shape of the curves that Gullicks proposed below an ammonia concentration of 15 mgN/L.

The curves arbitrarily developed by Gullicks have been approximated by a two-variable quadratic function (Equation 9) in order to determine which model, Gullicks or Gujer and Boller, does a better job of explaining the variability in the data. Data points were taken from the Gullicks' curves and a best fit, response surface function was fit to these points using JMP© statistical software. The equation that estimates Gullicks' curves explains 95% of the variability in Gullicks' curves. This function only applies to the region occupied by Gullicks' curve, or operating conditions with a hydraulic loading of (0 , 2.0) L/s/m^2 and an ammonia influent concentration of (0 , 25) mgN/L.

$$j_n = -0.00041 + 0.0011\nu_H + 4.9*10^{-5}S_{N,i} - 0.00046\nu_H^2 + 3.4*10^{-5}S_{n,i}\nu_H - 2*10^{-6}S_{N,i}^2$$

Equation 9

Note: ν_H units are (L/m^2/s) and j_n units are (kg/m^2/day) for Equations 9, 11 and 12.
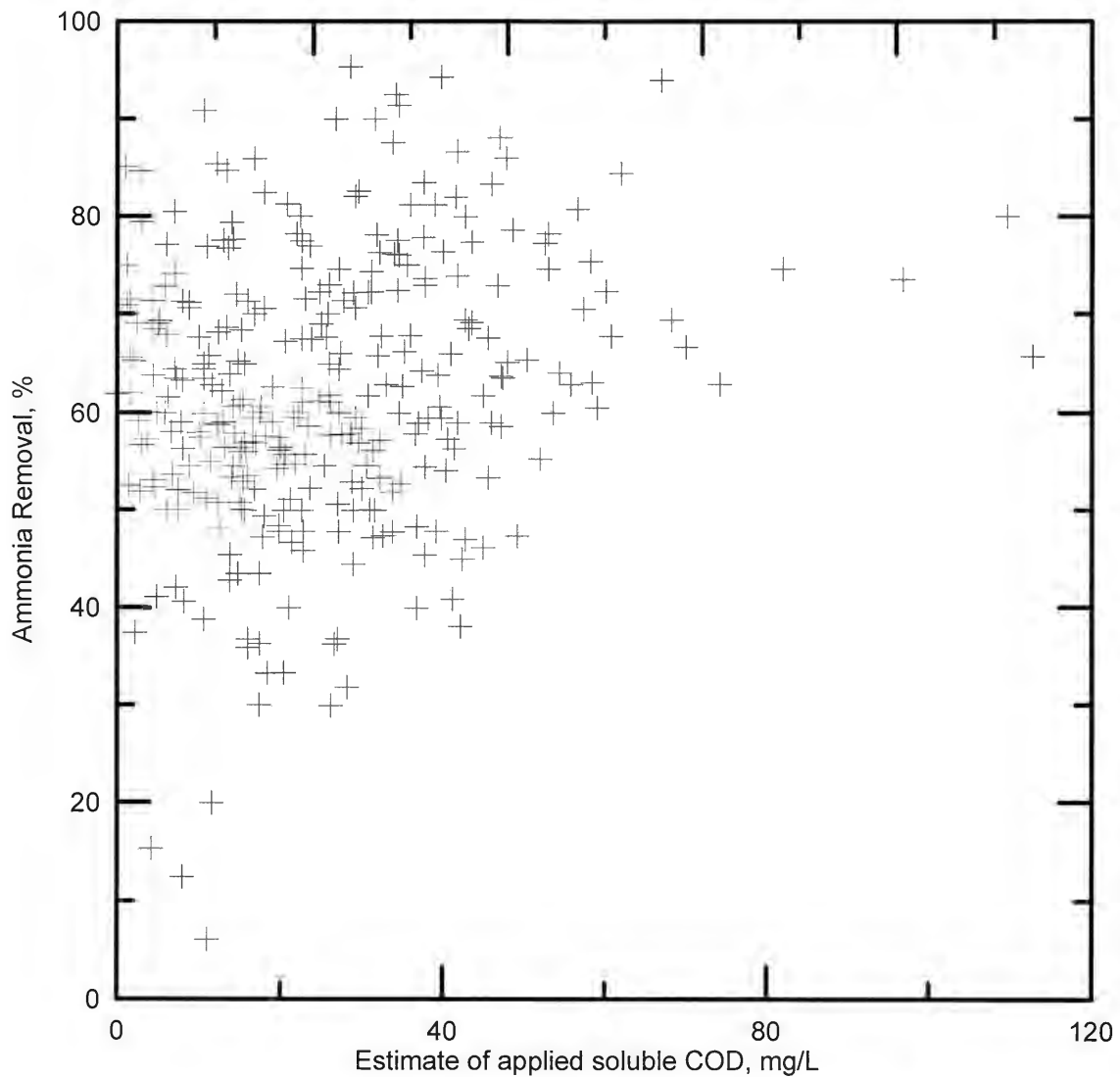
Figure 10. Ammonia removal percentage versus estimated soluble COD in AWPCF TFs.
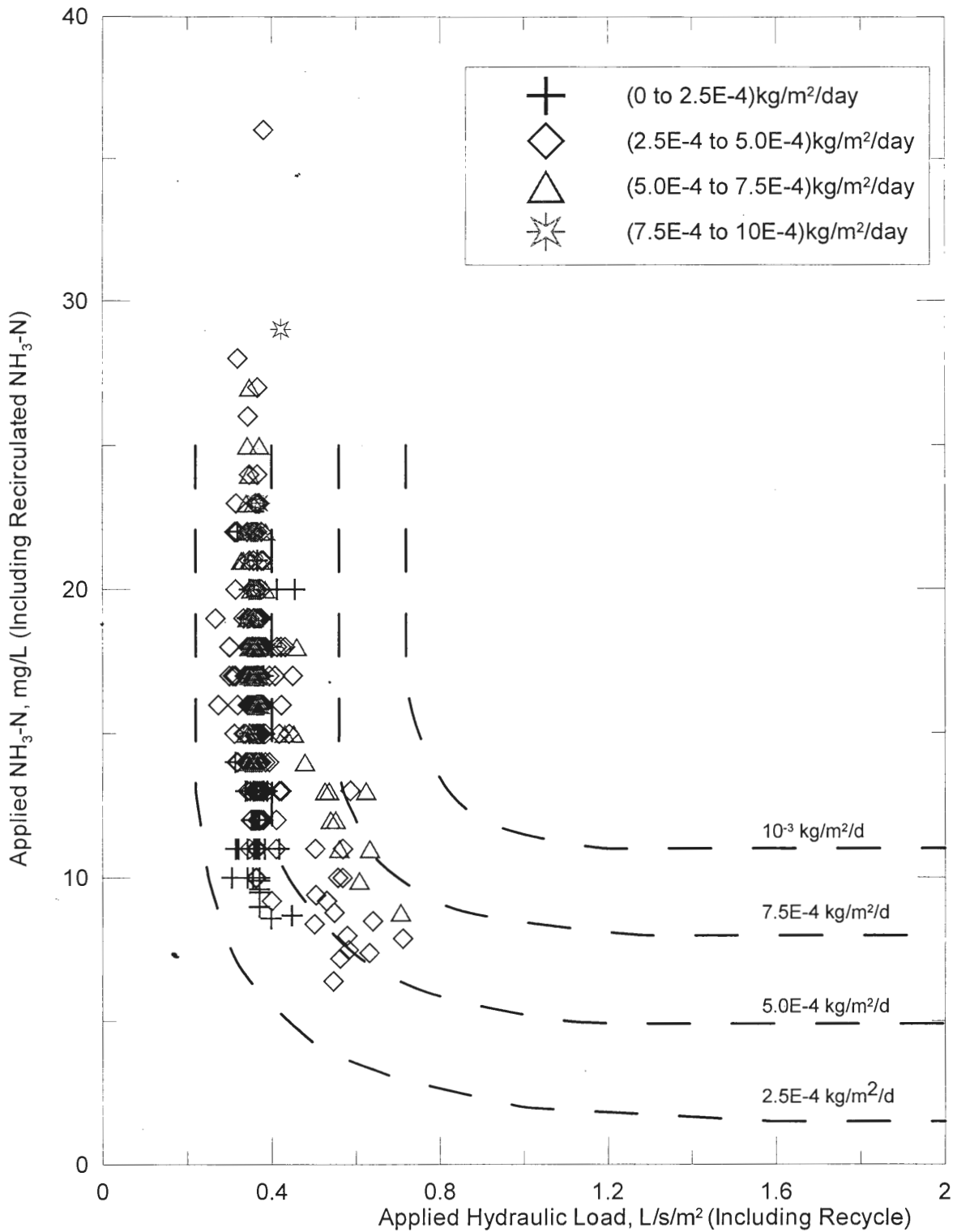
Figure 11. Operating data for TFs, ammonia removal rate adjusted to 10°C, superimposed over a replication of Gullicks' (1987) curves.

The two-variable quadratic equation, developed as an estimation of Gullicks' curves, can be contoured on a two-dimensional surface in the same manner as Gullicks' curves. The contours from the response surface equation have a similar shape to Gullicks' curves for the upper left hand portion of the curves. The right side of the curves, however, begins to rise rather than becoming asymptotic with an influent concentration as in both Gullicks' and Gujer and Boller's models.

The estimation equation was compared to Gullicks' data (data from Gullicks' PhD research) and to the operating data from the TFs. R^2 values were not available because of the data scatter. Therefore, coefficients of variability were measured to compare models. The coefficient of variability is the root mean square error for the prediction values divided by the mean of the data response values (Equation 10). A lower coefficient of variability indicates a better fit.

$$C_v = \frac{\sqrt{MSE}}{\bar{x}}$$
Equation 10

C_v = Coefficient of variability

MSE = Mean square error

$\bar{x}$ = Mean of the data for the response variable

The modified Gujer and Boller equation was regressed to the operating data set, data from the TFs, using a non-linear fit function in JMP© software. The Gujer and Boller equation was not calibrated to Gullicks' data set because the Gujer and Boller equation is

customized to a trickling filter's specific surface area and depth, and Gullicks' data set contained data from a number of different trickling filters. The regressed values found for the equation constants (Equation 8) were 0.78 $g/m^2/day$ for $j_{n,max}$ and 0.033 gN/m^3 for N. The coefficient of variability is 0.49. The value for $j_{n,max}$ may not be appropriate since higher removal rates have been observed. The value for $j_{n,max}$ should be the maximum observed ammonia removal in the top of the TFs.

The regressions show that the modified Gujer and Boller equation does a better job of explaining the variability for the operating data for specific ammonia removal, adjusted for temperature to 10°C, given hydraulic loading and influent ammonia concentration including recirculation effects (Table 3). The coefficient of variability for the Gujer and Boller model is roughly 1/2 the value of the coefficient of variability for the Gullicks' estimation for the operating data set.

An empirical equation was also developed using JMP© for both data sets. As a result, a two-variable quadratic equation was created that attempts to explain the variability in ammonia removal, adjusted to a 10°C basis, given hydraulic loading and influent ammonia concentration data. The empirical equation for Gullicks' data (Equation 11) has an R^2 value of 0.57 and a coefficient of variability of 0.38. The empirical equation for the operating data (Equation 12) has an R^2 of 0.34 and a coefficient of variability equal to 0.29 (Table 3). The empirical equations are not statistically similar at a significance level of $\alpha = 0.05$.

$$j_n = -0.000268 + 0.0006306 v_H + 4.28 * 10^{-5} S_{N,i} - 0.000138 v_H^2 + 1.54 * 10^{-5} S_{N,i} v_H - 10^{-6} S_{N,i}^2$$

Equation 11

$$j_n = -2*10^{-5} - 0.001075\nu_H + 4.15*10^{-5}S_{N,i} + 0.00219\nu_H^2 - 3*10^{-6}S_{N,i}\nu_H - 6.00*10^{-7}S_{N,i}^2$$

Equation 12

Table 3. Coefficients of variability for Gullicks curves, the Gujer and Boller model, and the empirical model.

Data Source	Gujer and Boller Model	Gullicks Model	Equation 11	Equation 12
Gullicks' Data	--	6.36	0.38	--
Operating Data	0.49	1.06	--	0.29

Note: A lower coefficient of variability indicates a better fit.

Experimental Data

Extant respirometry test

Kinetic testing was performed on the mixed liquor suspended solids (MLSS) from the solids contact process. A majority of the biomass in the solids contact is from sloughing of the trickling filters, and the respirometry tests of the autotrophs in the solids contact aeration basin provide insight to the kinetic coefficients of the biofilm in the trickling filters. The analysis method followed was developed by Riefler et al. (1998). The yield constant has been rewritten in terms of biomass generated per total ammonia consumed for comparison basis. The test was conducted on one sample. The background respiration rate was too high to distinguish the nitrification curve. A fed batch experiment was run in which the endogenous respiration rate was slowed, without affecting the nitrifiers, by maintaining the

nitrifiers and not heterotrophs. The results (Table 4) are consistent with the kinetic constants provided by Davis and Cornwell (1998).

Table 4. Monod kinetic constants for nitrification in the solids contact process at AWPCF at 25°C.

Source	Yield (mgVSS/mgNH$_4^+$-N)	K_s (mgN/L)	$\mu_{max}X^*$ mg/L/hr	μ_{max} 1/hr
Extant Respirometry Results	0.23	2.15	1.92	--
Davis/Cornwell	0.17	1.4	--	1.003

* Competent biomass fraction for nitrification not known therefore only a total growth rate could be determined.

Nitrification

Nitrification in the trickling filters was confirmed by comparing the nitrates that were generated to the ammonia that was consumed. The ammonia removal mechanism is predominantly nitrification if the difference between the ammonia consumed and nitrates generated is small. A plot (Figure 12) showing ammonia removal versus nitrates generated should have a slope of one if the nitrogen is balanced, and the only removal mechanism is nitrification. The best fit for the data with a y-intercept forced to equal zero yields a slope of 1.1 with an R^2 equal to 0.995. A 95% confidence interval was developed for the slope. The interval is (1.05 , 1.19).The slope of 1.1 indicates that more nitrates are being generated than ammonia is being consumed; i.e. if 20 mgNH$_3$-N/L that are consumed, 22 mgNO$_3^-$-N/L will be generated. The additional nitrates measured may be due to measurement errors of either

ammonia or nitrates, or additional nitrification of the ammonia generated from

ammonification of organic nitrogen.
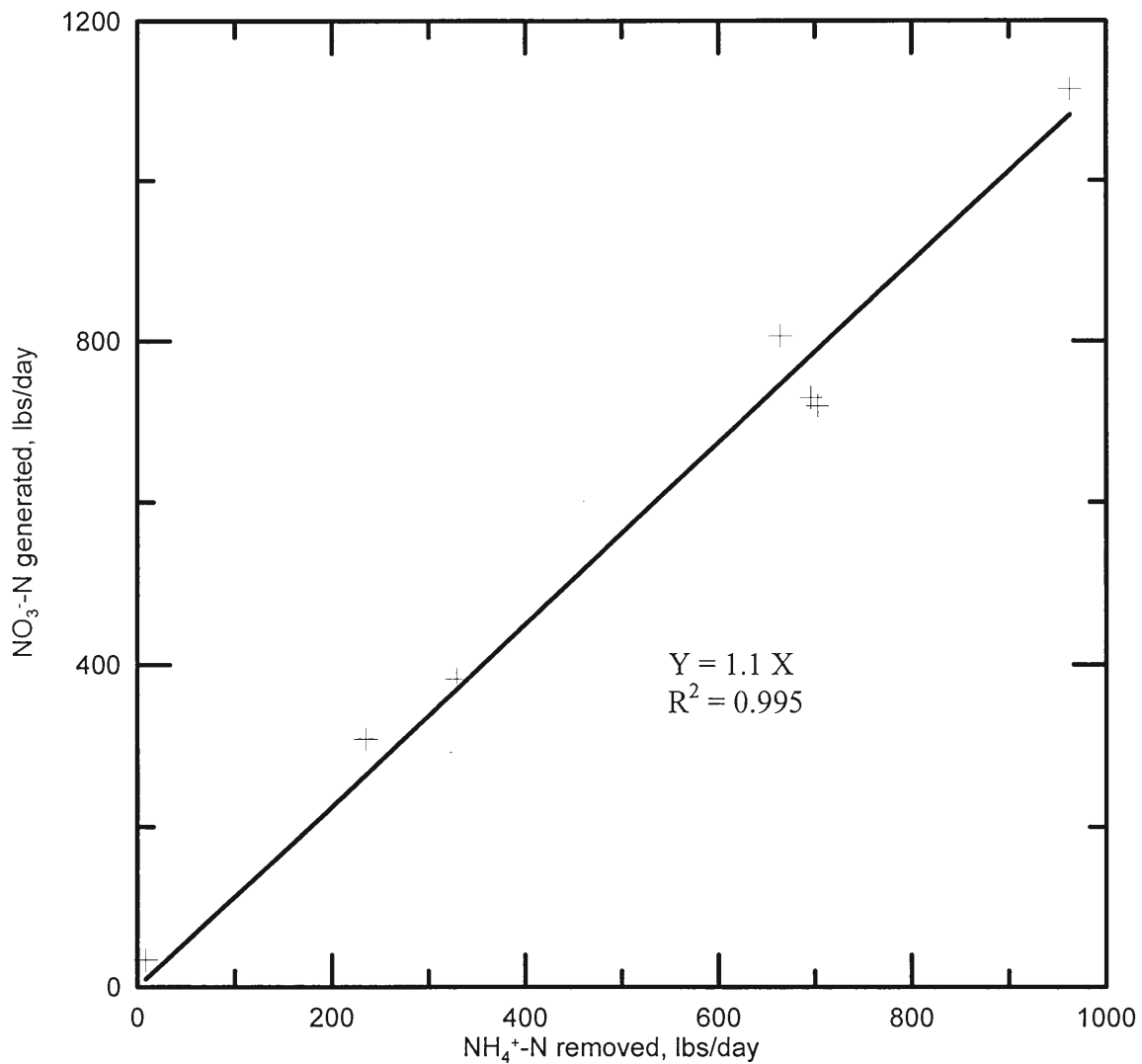
Figure 12. Plot of nitrates generated versus ammonia removed for eight samples obtained between 12/16/01 and 2/09/02.

Trickling filter data

Experimental data for the project were obtained between January and February of

2002 (Figure 13). The data show a similar pattern to the operating data and Gullicks' curves.
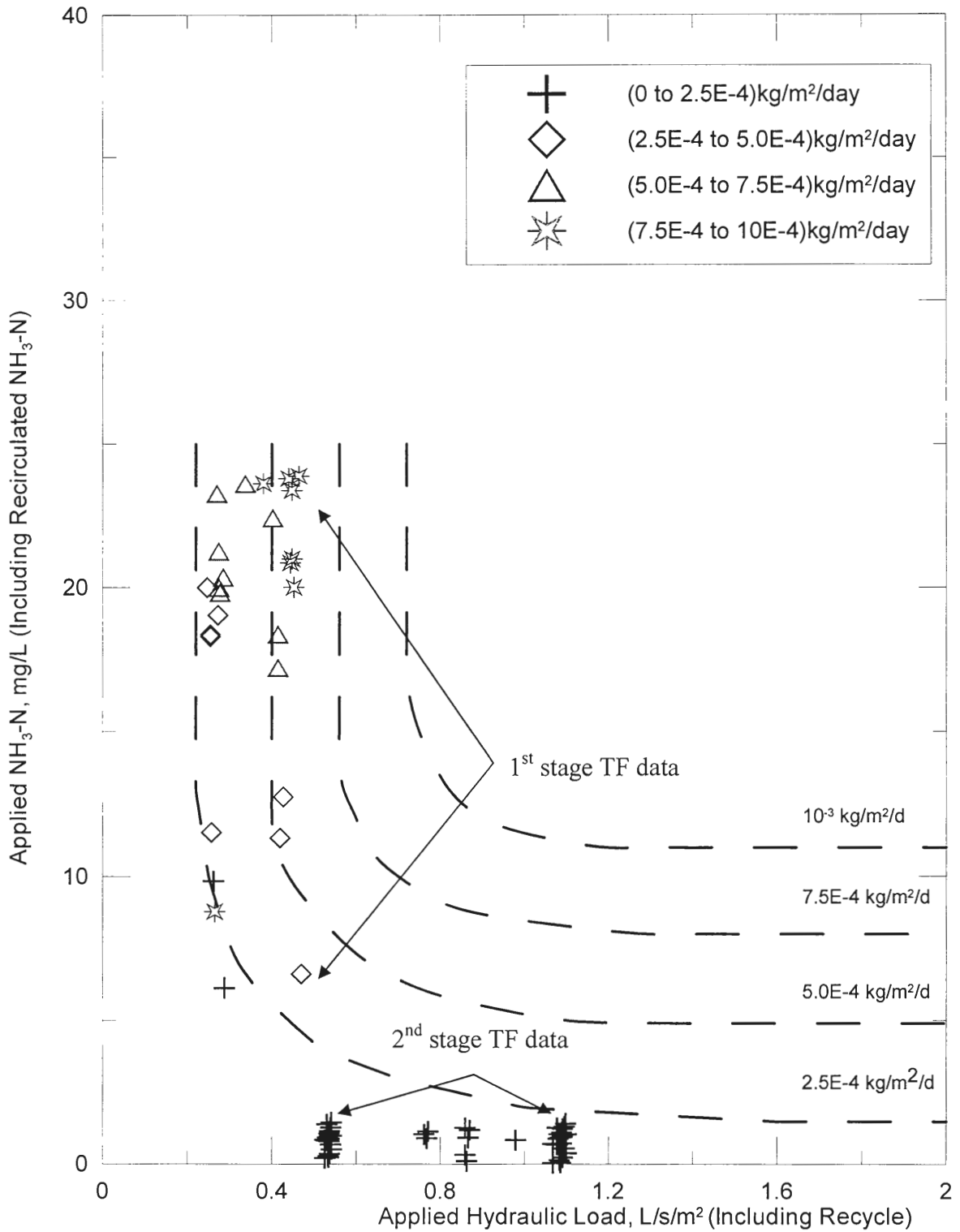
Figure 13. Experimental data, ammonia removal rates adjusted to 10°C, plotted against a replication of Gullicks' (1987) curves.

The TF data have higher influent concentrations than the NTF data and are on the left side of the plot. The NTF data show influent concentrations of 1 mgN/L or less and are on the bottom of the plot. A replication of Gullicks' curves has been superimposed over the data for reference purposes. The experimental data were compared to the estimation equation of Gullicks' curves. The estimation equation explains 55% of the variability in the experimental data; i.e. it has an R^2 of 0.55.

The experimental data were used to improve model calibrations. The Gujer and Boller model is specific to the TFs or NTFs. The experimental data for the TFs were added to the operating data to improve this calibration. The experimental data did not improve the Gujer and Boller model for the TFs, because the data were limited (Table 5).

The experimental data were all that was available for the NTFs since ammonia removal rates cannot be calculated when the effluent ammonia concentration is below the AWPCF's laboratory detection limit. The data provide little insight into the shape of the curve since the NTFs are underloaded. The defaults given by Gujer and Boller (1986), $j_{n,max}$ = 0.85g N/m^3/day and N = 1.0 gN/m^3, were input into the model and the closeness of fit measured. The closeness of fit for the NTFs appears significant (Table 5), but the limited data do not provide a good picture of the true removal relationship with the operating variables.

A new empirical equation (Equation 13) was developed with the addition of the experimental data. The equation is regressed to data from Gullicks' study, from operations between January 1999 and December 2001, and from the experimental data. The calibration is not specific to a trickling filter. It remains generalized without trickling filter dimensions. The R^2 for the new equation (Equation 13) is 0.60.

The models have been tested with common operating conditions to judge appropriateness (Table 6). The first stage TFs were assumed to have an ammonia influent concentration of 20 mgN/L and a flow rate of 5,000 gallons per minute (gpm) or a hydraulic loading of 1.00 gpm/ft^2. The Gujer and Boller model, calibrated for the TFs, predicts an effluent concentration of 0.17 mgN/L. The two-variable quadratic equation predicts an effluent concentration of 0.6 mgN/L. Both predictions are lower than the actual data.

The second stage NTFs were assumed to have an ammonia influent concentration of 5 mgN/L, a high value, and a flow rate of 12,000 gpm or a hydraulic load of 2.40 gpm/ft^2. The Gujer and Boller model, calibrated for the NTFs, predicts an effluent concentration of 0.22 mgN/L. The two-variable quadratic equation predicts a negative effluent concentration. A negative value is unrealistic and the Gujer and Boller model may be more appropriate.

$$j_n = -0.000361 + 0.000642\upsilon_H + 4.27*10^{-5}S_{N,i} - 0.000142\upsilon_H^2 + 1.7*10^{-5}S_{N,i}\upsilon_H - 9.19*10^{-7}S_{N,i}^2$$

Equation 13

Note: ν_H units are (L/m^2/s) and j$_n$ units are (kg/m^2/day) for Equation 13.

Table 5. Gujer and Boller model calibrations.

Trickling Filters	Data Source	$j_{n,max}$	N	C_v	R^2
Stage 1	Operating Data	0.78	0.033	0.49	--
Stage 1	Operating Data & Experimental Data	1.5	0.1	0.53	--
Stage 2	Experimental Data	0.85*	1.0*	0.27	0.67

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

Table 6. Example of model predictions for general operating conditions.

Model	Trickling Filters	Influent NH_3-N Concentration (mgN/L)	Hydraulic Loading (gpm/ft^2)	Predicted Effluent NH_3-N Concentration (mgN/L)	Actual Effluent NH_3-N Concentration (mgN/L)
Gujer and Boller	Stage 1	20.0	1.00	0.17	5.0*
Equation 13	Stage 1	20.0	1.00	0.6	5.0*
Gujer and Boller	Stage 2	5.0	2.40	0.22	<0.5**
Equation 13	Stage 2	5.0	2.40	-2.2	<0.5**

*Actual values for stage 1 trickling filter effluent ammonia concentration based on operating data from 15th January, 2002.
**Actual values for stage 2 trickling filter effluent ammonia concentration based on operating data from 27th January, 2002.

CHAPTER 5. DISCUSSION

AWPCF Characteristics

The AWPCF is highly effective at treating wastewater from the City of Ames using a two stage trickling filter process with a solids contact process. The city personnel anticipate an increase in ammonia loading during the next decade and requested a study to find the nitrifying capacity of their treatment facility. The results listed in the previous section reveal a number of useful characteristics and help to elucidate the treatment capabilities of their treatment processes.

The overall yield for the AWPCF was found to average 0.20 mgVSS/mgCBOD over a 15 month period. Trickling filter treatment processes have a lower yield typically as a result of the long residence time in the trickling filter for solids whereby endogenous decay reduces the amount of solids wasted from the trickling filter. "Sludge ages over 100 days can be easily attained (Droste, 1997)." Longer solids retention times (SRT) allow for development of a diverse microbial environment and higher organisms. A long SRT is vital to nitrification due to the slow growth rate of the autotrophic bacteria involved.

Nitrifying bacteria have kinetic characteristics and constants that uniquely differ from the grouped heterotrophic characteristics. The respirometry test confirmed the presence of the nitrifiers, and verified their kinetic constants for the solids contact aeration basin. The kinetic constants found in the respirometry test were similar to those given by Davis and Cornwell (1998). If the competent biomass fraction was 10 mg/L, estimated from an assumed yield, then the maximum specific growth rate will be 0.19 hr^{-1}. The yield values

average to 0.225 mgCBOD/mgCBOD. The low growth rate and the low microbial yield are classic characteristics of the autotrophic bacteria involved in nitrification.

Researchers have hypothesized that biofilms in trickling filters are heterogeneous and complex structures with specialized layers (Noguera et al., 1999a). Faster growing non-selective organisms can easily flourish on the top layers of the biofilm while specialized slower growing species subsist deeper in the biofilm. This is a reasonable theory that can be applied to nitrification in the AWPCF's TFs. Nitrifiers are displaced from a biofilm by heterotrophs because they have a lower growth rate and cannot compete for space. Given space, heterotrophs and nitrifiers compete only for oxygen. As long as the trickling filter is an efficient gas exchanger, nitrifiers and heterotrophs should be able to coexist. The heterotrophs would be preferentially selected to grow on the outer layers of the biofilm due to their higher growth rate. Nitrifiers will persist once the organics are consumed or cannot penetrate any deeper, as long as oxygen, a carbon source, and ammonia can penetrate.

The study at AWPCF shows consistently high ammonia removal rates in the TFs. This would support the hypothesis of simultaneous nitrification and CBOD removal in a single stage trickling filter. It does not show whether nitrification is occurring due to a layered biofilm whereby nitrifiers persist beneath heterotrophs, or solely in the lower depths of the trickling filter after the CBOD has been removed. In order to determine the mechanism, samples may be taken at various depths along the profile of the TFs to show the ammonia removal by section, or nitrifiers may be quantified and compared at different locations within the trickling filter. The mechanism by which ammonia is removed in the first stage trickling filters was not determined in this study.

Another interesting characteristic of the AWPCF concerns the affect of solids handling on different flow schemes. Short circuiting of flow occurs if the solids contact is set as the last process in the flow scheme. The underflow from the intermediate clarifiers is pumped into the aeration basin directly thus bypassing the NTFs. The short circuiting causes a slight increase in ammonia concentration in the flow from the effluent of the NTFs to the final effluent.

Nitrifying Trickling Filter Removal Predictions

A number of models are now available to help predict the rate of nitrification in trickling filters. All of the models are conservatively intended for use at 10°C. The design model developed by Gullicks as stated by Gullicks (2001) was intended "…to provide a conservative basis for cold-climate winter operation design…" for nitrifying trickling filters. While the model provides a good basis for design, it does a poor job of predicting ammonia removal under the AWPCF's current normal operating conditions. The model developed by Gujer and Boller does a better job of predicting performance as judged by the coefficient of variability and is most appropriate for the NTFs.

The best model for the TFs may be an empirical model developed using statistical regression. This model incorporates the hydraulic loading and influent ammonia concentration with recirculation effects, the operating variables most important to predicting performance, into a two-variable quadratic function designated a response surface by JMP©. The model is only valid for the range in which data points are available, and it applies directly to the data from which it was derived. Hence, when operating data and experimental

results from this study are used to generate an equation, then it is most applicable to AWPCF trickling filters. The Gujer and Boller model, on the other hand, is based on theory and is applicable to all similar trickling filters. The Gujer and Boller model should be used for extrapolating beyond the range of the data due to its theoretical basis. The Gullicks' design curves still provide an appropriate basis for design, but may be excessively conservative resulting in unnecessary over design and capital expenses.

Predictions of ammonia removal throughout the AWPCF have been made for design ammonia loading conditions assuming other conditions do not change and the current model calibrations are valid. The empirical equation (Equation 13) was used for TFs predictions assuming the current first stage pump flow rate and calculated recirculation effects. The solids contact process was conservatively assumed to remove no ammonia. This may be true at times due to the short solids retention time (SRT). The solids are sloughed and eroded from the trickling filters, however, and the system SRT is generally much longer, therefore allowing ammonia removal in the solids contact process. The calibrated Gujer and Boller model was used for NTFs predictions accounting for recirculation effects. The predictions for both stages of the trickling filters must be iterated since the influent concentration is dependent on the effluent concentration due to recirculation. The conditions, inputs, and outputs are listed in Table 7.

The Gujer and Boller model was also used to predict the ammonia effluent concentration for the second stage trickling filters if the second stage trickling filters receive the entire design ammonia load. The model predicts 6.5 mgN/L to be the effluent ammonia concentration. The two-variable, quadratic equation (Equation 13), on the other hand,

predicts full removal of ammonia. The Gujer and Boller model should be recalibrated with a more complete set of data from the second stage trickling filter.

Table 7. Ammonia effluent predictions for design conditions at the AWPCF.

Process	Flow, MGD	Model	Influent NH_3, mgN/L	Effluent NH_3, mgN/L
Overall for facility	8.6	--	27.5	< 0.5
1st stage TFs	8.6	Two-variable quadratic	27.5	4.5
Solids contact*	8.6	--	4.5	4.5
2nd stage NTFs	16.5	Gujer and Boller	2.3	0.004

*Nitrification in solids contact neglected due to low solids retention time.

The two-variable quadratic equation has been adjusted to English units and algebraically manipulated (Equation 14) for ease of use by AWPCF operators for direct application to the TFs. The inputs required are the trickling filter influent concentration, in mgN/L and adjusted for recirculation, and the flow rate, in gpm. The output is the effluent ammonia concentration, in mgN/L, for the TFs. A basic set of curves (Figure 14) was then developed using Equation 14. The TFs ammonia effluent concentration can be found from the curve. Simply follow the hydraulic loading (total applied load) up from the x-axis to the appropriate influent concentration curve (adjusted for recirculation) and over to the effluent concentration (y-axis). A set of curves (Figure 15) was also developed for the TFs using the calibrated Gujer and Boller model. The Gujer and Boller model curves are more appropriate for extrapolating beyond the range of the data used to regress Equation 14.

$$S_e = S_i + \frac{48,300}{q} - 5,680\frac{S_i}{q} - 11.56 + 123\frac{S_i^2}{q} - 0.31S_i + 0.000336q$$

Equation 14

S_e = Effluent ammonia concentration, mgN/L

S_i = Influent ammonia concentration, mgN/L

q = Trickling filter flow rate with recirculation, gpm
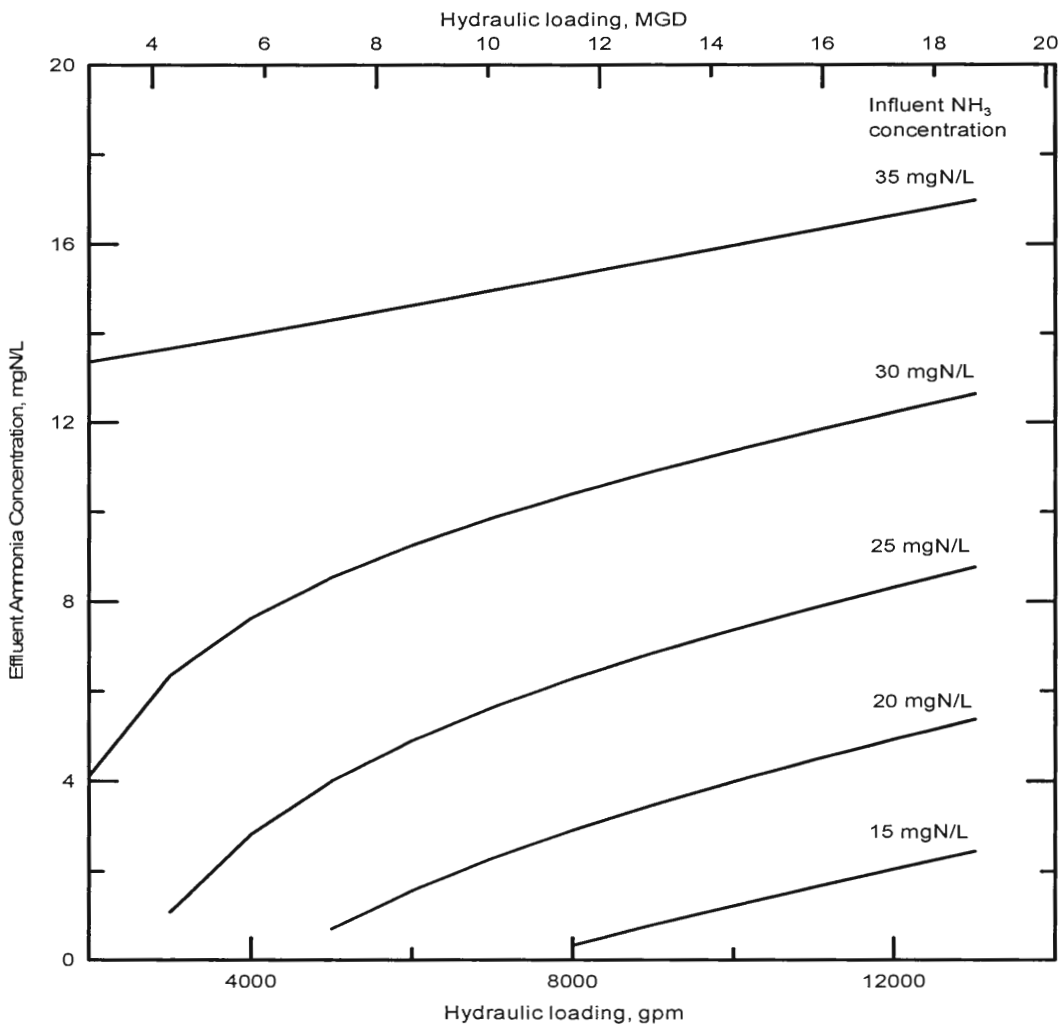
Figure 14. Curves for predicting the effluent ammonia concentration in the TFs based on the empirical regression.
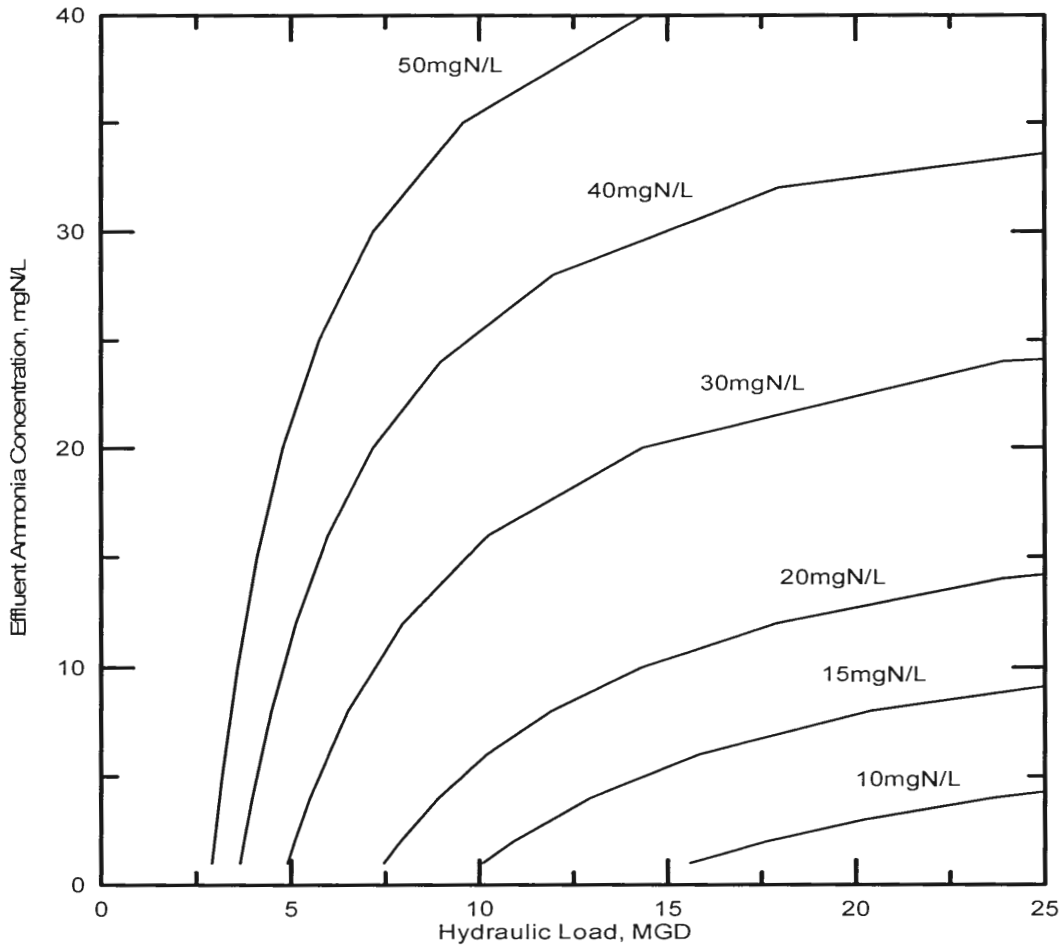
Figure 15. Curves for predicting the effluent ammonia concentration in the TFs based on the calibrated Gujer and Boller model.

Predictions for ammonia removal beyond the design loading (Table 8) were made to give insight into the maximum nitrifying capability at the AWPCF. The predictions were made using the calibrated Gujer and Boller model, because extrapolation beyond the data range is inappropriate for Equation 14. The assumptions for these predictions are that the solids contact process does not remove ammonia and the nitrifying characteristics of the TFs do not change significantly. Table 8 shows that the combined removal of the TFs and NTFs is adequate to meet effluent ammonia mean monthly winter permit requirements (5.7mgN/L)

for an influent wastewater flow of 12 million gallons per day (MGD) with an influent

ammonia concentration of 27.5 mgN/L.

Table 8. Ammonia removal predictions beyond design loading.

Raw Influent			Stage 1 TFs*		Stage 2 TFs**	
Flow, MGD	Ammonia, mgN/L	Loading, lbsN/day	Influent NH_3	Effluent NH_3	Influent NH_3	Effluent NH_3
8.6	27.5	1972.41	17.5	10.5	4.2	0.5
10	27.5	2293.5	20.2	13.2	7	2.3
12	27.5	2752.2	22.6	15.6	10.7	5.5
14	27.5	3210.9	24.3	17.3	13.8	8.6
16	27.5	3669.6	25.6	18.6	16.1	10.7
18	27.5	4128.3	26.6	19.6	18	12.5
20	27.5	4587	27.4	20.4	19.5	14

Note: All ammonia concentrations reported as mgN/L.
*Total flow to stage 1 TFs is 20.4 MGD. Gujer model used for predictions.
**Total flow to stage 2 TFs is 23.4 MGD. Gujer model with default constants used for precitions.

CHAPTER 6. CONCLUSION

Engineering Significance

The current AWPCF has excelled in wastewater treatment since it went into full operation over a decade ago. The operators professionally maintain the facilities to the highest standard every day. The final effluent quality is consistently good, and the facility has not had a permit violation.

A number of useful observations have been made using the data generated by the nitrification study performed at the AWPCF. The study follows up the work performed by Gullicks and Cleasby (Gullicks, 1987) during the middle 1980s. The goal was to determine the actual ammonia removal capacity for the facility and reconcile the new findings with previous models. A number of Gullicks' findings have been affirmed. An improved, empirical ammonia removal prediction model, customized for the AWPCF, has been developed for the TFs based on operating and experimental data.

Operating and experimental data have been used to compare actual specific ammonia removal rates at the AWPCF with the curves developed by Gullicks (1987). Gullicks' curves follow the general trend suggested by the data, but fit poorly to the data as judged by the coefficient of variability. The curves may be conservatively used, as intended, for the design of an ammonia removal trickling filter under cold-weather conditions. Gullicks' curves are not appropriate for predicting the actual removal of ammonia at the AWPCF.

The model developed by Gujer and Boller (1986) has been calibrated using operating and experimental data. Their model has the best fit to the NTFs, and is appropriate to predict

the ammonia effluent concentration for AWPCF trickling filters, especially the NTFs. Though intended for NTFs, the model may also be useful in roughly estimating the ammonia removal for the TFs.

An empirical model, a two-variable quadratic equation also called a response surface, has been developed using statistical regression in JMP©. This model incorporates the four variables suggested by Gullicks (1986) to be the most important in determining ammonia removal in trickling filters. The model has been written explicitly for specific ammonia removal at 10°C as a function of hydraulic loading and ammonia influent concentration both adjusted for recirculation. The model does the best job of predicting ammonia removal rates of the models given for the TFs. The model is appropriately used for predicting ammonia removal in the TFs at the AWPCF within the range of the predictor variables.

Total ammonia removal for the AWPCF has been predicted under a number of operating conditions. The removal predictions assume mode four of operation whereby the order of biological treatment processes is stage one TFs, solids contact process, and stage two TFs. Another assumption is that all other variables within the processes do not significantly change. According to predictions, the facility is capable of meeting current effluent ammonia requirements for the total ammonia load for which it was designed.

Many of the findings are consistent with Gullicks' study (1987). The ammonia removal capacity of the TFs is perhaps the most interesting finding. It is not known if ammonia is removed simultaneously at the same depths as CBOD removal, if ammonia is not removed until a deeper depth within the trickling filter after the CBOD has already been removed, or a combination of both. A future study incorporating sampling ports along the

trickling filter to profile ammonia and CBOD/COD removal with depth would provide valuable insight to understanding if ammonia and CBOD removal can occur simultaneously.

The study of full scale nitrifying trickling filters presents many interesting challenges. Data along the depth of the trickling filter is useful. A data profile allows for an understanding of what is happening within the trickling filter. It answers questions such as:

- Does ammonia removal rate increase or decrease with depth?
- Does nitrification occur simultaneously with CBOD removal?
- If ammonia removal occurs simultaneously, does the rate increase or decrease with soluble COD concentrations?

The answers to these questions may vary with each trickling filter depending on local climate, type of media, gas exchange efficiency of the trickling filter, wastewater characteristics, dosing rate and controls, etc.

A number of factors make studying a full scale facility difficult. The facility's first priority is treating the wastewater and meeting permit requirements. The operators wisely avoid dramatic changes to their processes and operating conditions. Underloaded trickling filters cannot be easily studied for full ammonia removal capacity. Ammonia concentration cannot be profiled at different depths along the trickling filter without sampling ports, but installing sampling ports endangers the structural integrity of the trickling filters.

The City of Ames has done an excellent job of accommodating the research on this project to satisfy the project objectives. The results reveal that the wastewater treatment facility will perform better than design predictions with respect to nitrification. The AWPCF

has the capacity to remove ammonia according to projected loadings for the year 2010. The first stage trickling filters are removing a significant fraction of the ammonia thus enhancing the facilities overall ammonia removal capacity.

Hypotheses were made at the beginning of the study concerning nitrification in the AWPCF trickling filters, and conclusions have been made about the hypotheses based on the results of the study.

- The first stage trickling filters are removing a significant fraction of the ammonia loading at the facility. The operating data does not show that an increase in organic loading negatively affects the ammonia removal capabilities.

- The influent ammonia concentration, wastewater temperature, hydraulic loading, and recirculation rate explain less than 70% of the variability in specific ammonia removal rates as applied in the models. The additional variability has not been explained.

- Gullicks' curves (1987) do a poor job of predicting the effluent ammonia concentration at the AWPCF. The curves conservatively estimate ammonia removal.

- The Gujer and Boller (1986) model has been poorly calibrated to the first stage trickling filters. A calibration could not be performed to the second stage trickling filters due to the limited data available.

- An empirical, two-variable quadratic equation does the best job of explaining the data. The empirical equation is appropriate for predicting effluent ammonia concentrations for the first stage trickling filters within the range of hydraulic loadings and influent ammonia concentrations for which the data was collected.

Future Research

Future research in nitrifying trickling filters can answer a number of questions and assist in expanding model development and removal predictions. Nitrification has been shown to occur simultaneously with CBOD removal in first stage trickling filters. The nature of the simultaneous removal should be examined and interpreted. With this knowledge, trickling filters may be designed for simultaneous removal preventing the need for additional treatment processes.

The AWPCF has the potential for a number of future studies or investigations for advanced treatment. With the proper adjustments or additions, the facility may be capable of nutrient removal through denitrification and biological phosphorus removal. Denitrification converts the nitrates, or end product of nitrification, to nitrogen gas. Nitrates are toxic to humans and cause methemoglobinemia. Denitrification is beneficial to the wastewater treatment facility since it recovers alkalinity and helps maintain the proper pH while removing nitrogen from the water.

Nitrogen, as ammonia or nitrates, and phosphorus are both limiting nutrients for growth of algae and other microorganisms. Their removal prevents massive growth which can choke the higher organisms in the receiving streams. Biological nutrient removal is becoming more common, and may eventually be the minimum standard.

The research performed in this project is very valuable to understanding the characteristics of nitrification at full-scale trickling filter facilities. Continuing research improves the engineering knowledge base and helps the AWPCF to maintain high operations standards and stay ahead of ever changing treatment guidelines. Treatment requirements

change to meet the demands of society and alleviate the burden on receiving streams. The
City of Ames and Iowa State University have a unique relationship that allows both entities
to benefit from applied research.

APPENDIX A. AWPCF PHOTOS AND DIAGRAMS

Figure A1. AWPCF trickling filters: NTFs are in the foreground and TFs are in the background.

Figure A2. TFs 60° crossflow media with a specific surface area of 30 ft^2/ft^3.
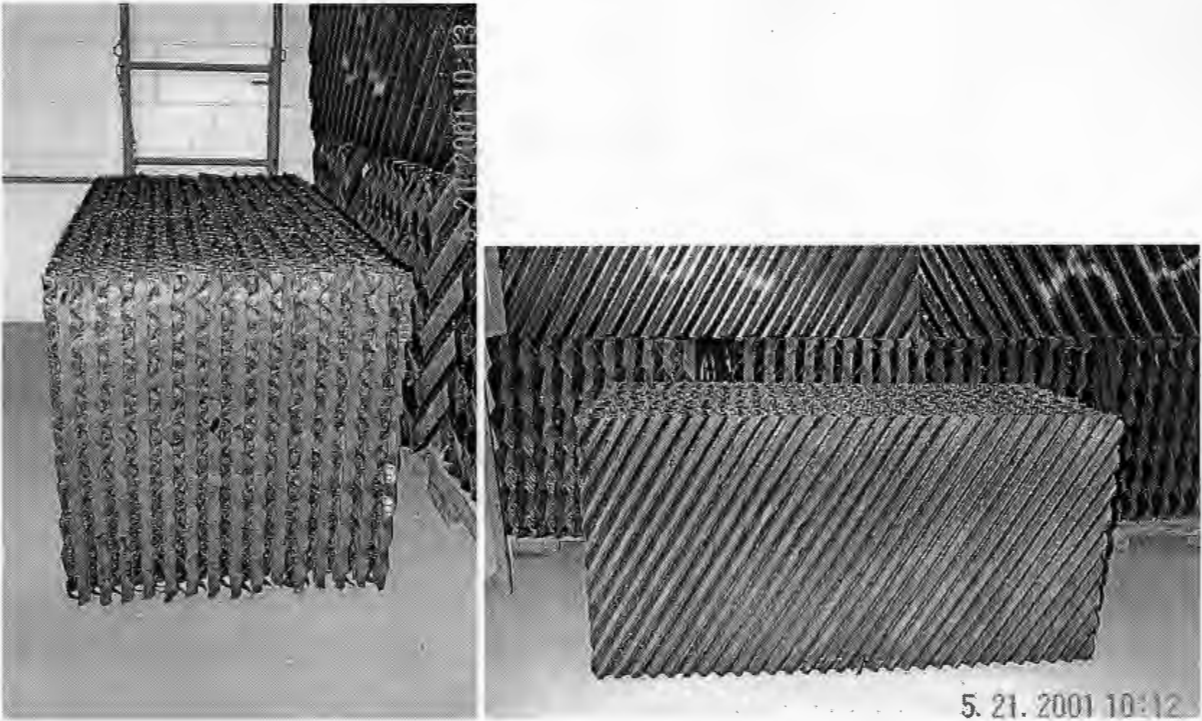
Figure A3. NTFs 60° crossflow, plastic media with a specific surface area of 50 ft^2/ft^3.
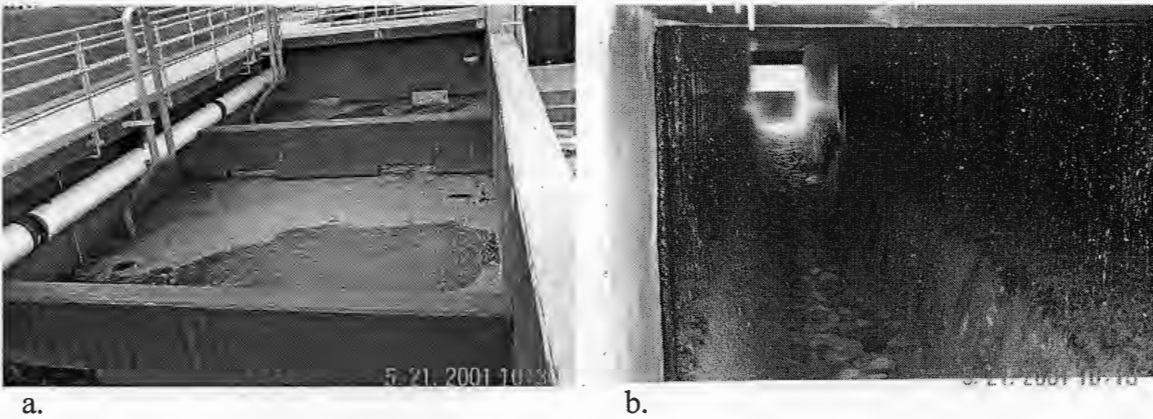
a.   b.

Figure A4a. Solids contact aeration basin.

Figure A4b. Trickling filter effluent channel.
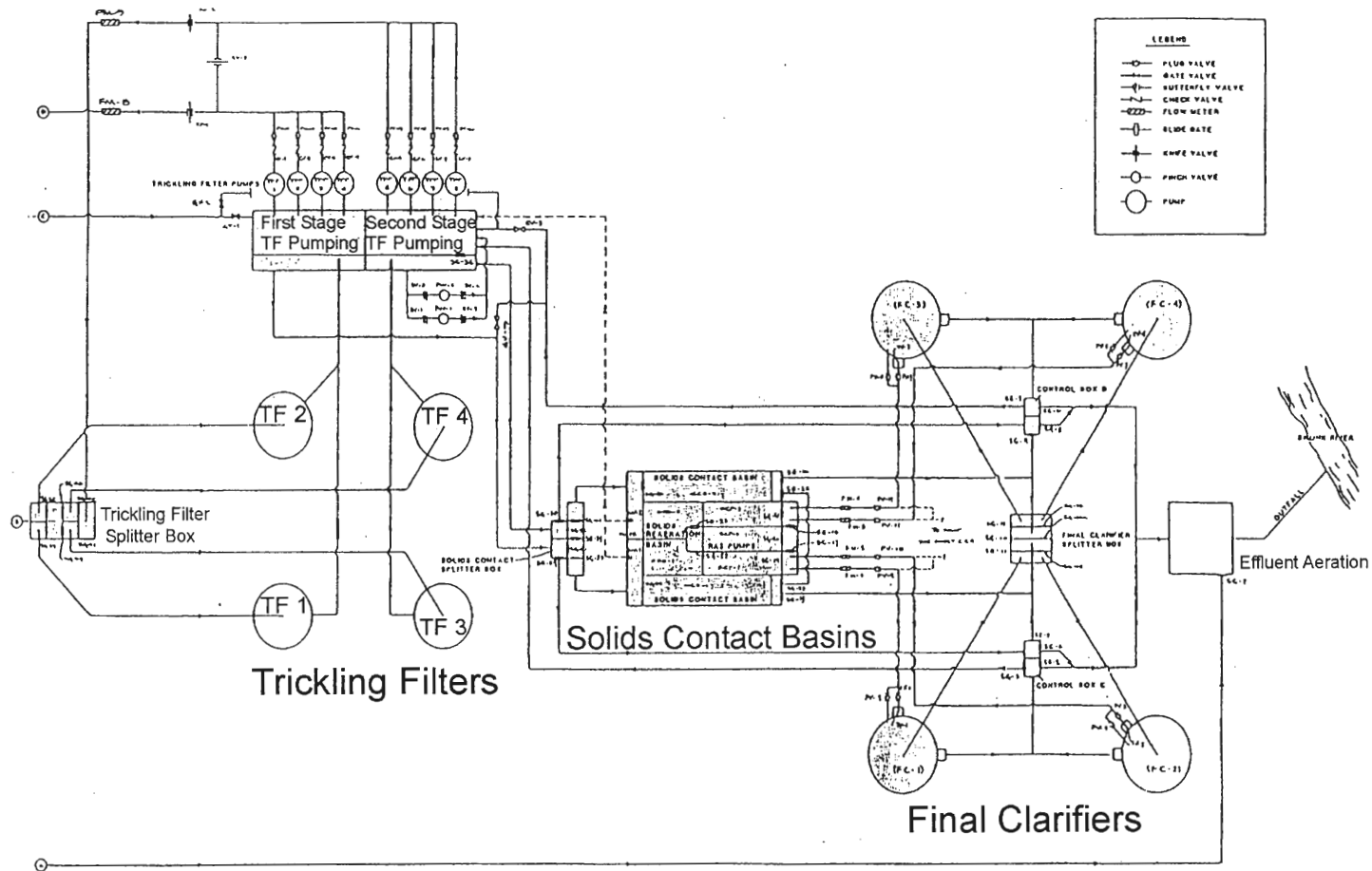
Figure A5. AWPCF process flow schematic for trickling filters, solids contact, and final clarification (Courtesy AWPCF).

APPENDIX B. RAW DATA

Table B1. Gullicks data set (Gullicks, 1987).

Hydraulic Load, L/m^2/s	Influent Ammonia, mgN/L	Ammonia Removal kgN/m^2/day, 10°C	source
0.468	4.7	2.23E-04	Ames nitrifying biofilter
0.458	1.6	8.16E-05	Ames nitrifying biofilter
0.461	2.6	1.43E-04	Ames nitrifying biofilter
0.461	2.6	1.35E-04	Ames nitrifying biofilter
0.517	7.3	3.27E-04	Ames nitrifying biofilter
0.503	6.1	3.03E-04	Ames nitrifying biofilter
0.506	3.6	2.16E-04	Ames nitrifying biofilter
0.503	6.4	3.08E-04	Ames nitrifying biofilter
0.503	5.7	3.29E-04	Ames nitrifying biofilter
0.58	9.7	3.51E-04	Ames nitrifying biofilter
0.581	10.7	4.47E-04	Ames nitrifying biofilter
0.581	11.5	3.88E-04	Ames nitrifying biofilter
0.577	7.3	2.55E-04	Ames nitrifying biofilter
0.583	11.8	3.03E-04	Ames nitrifying biofilter
0.584	16.7	4.52E-04	Ames nitrifying biofilter
0.58	12.5	3.80E-04	Ames nitrifying biofilter
0.577	9.3	3.26E-04	Ames nitrifying biofilter
0.581	11.7	4.14E-04	Ames nitrifying biofilter
0.583	10.5	4.10E-04	Ames nitrifying biofilter
0.581	10.9	2.91E-04	Ames nitrifying biofilter
0.584	9.6	4.04E-04	Ames nitrifying biofilter
0.584	5.7	3.44E-04	Ames nitrifying biofilter
0.584	7.9	2.76E-04	Ames nitrifying biofilter
0.584	9.5	1.59E-04	Ames nitrifying biofilter
0.584	6.6	2.94E-04	Ames nitrifying biofilter
0.568	7.6	3.47E-04	Ames nitrifying biofilter
0.577	10.6	4.57E-04	Ames nitrifying biofilter
0.574	15.7	5.42E-04	Ames nitrifying biofilter
0.529	12.7	5.33E-04	Ames nitrifying biofilter
0.589	20.1	3.04E-04	Ames nitrifying biofilter
0.571	13.5	2.74E-04	Ames nitrifying biofilter
0.578	11.8	4.15E-04	Ames nitrifying biofilter
0.578	8.7	2.71E-04	Ames nitrifying biofilter
0.56	19.2	3.20E-04	Ames nitrifying biofilter
0.563	21.2	2.90E-04	Ames nitrifying biofilter
0.571	18.1	4.50E-04	Ames nitrifying biofilter
0.783	11.6	3.31E-04	Ames nitrifying biofilter
0.775	12.2	3.23E-04	Ames nitrifying biofilter
1.17	11.3	1.59E-04	Ames nitrifying biofilter
1.16	9.7	1.58E-04	Ames nitrifying biofilter

Table B1. (Continued)

Hydraulic Load, L/m^2/s	Influent Ammonia, mgN/L	Ammonia Removal kgN/m^2/day, 10°C	source
1.137	9.9	1.44E-04	Ames nitrifying biofilter
1.271	10.6	4.76E-04	Ames nitrifying biofilter
1.243	10.8	5.38E-04	Ames nitrifying biofilter
1.37	5.3	5.73E-04	Ames Pretreatment Tower
1.37	2.6	5.58E-04	Ames Pretreatment Tower
1.41	5	7.08E-04	Ames Pretreatment Tower
1.43	8.5	6.65E-04	Ames Pretreatment Tower
1.37	6.4	4.23E-04	Ames Pretreatment Tower
1.9	3.9	7.16E-04	Ames Pretreatment Tower
1.91	6.9	1.05E-03	Ames Pretreatment Tower
1.9	4.1	9.98E-04	Ames Pretreatment Tower
1.89	0.8	2.89E-04	Ames Pretreatment Tower
1.9	8.6	1.10E-03	Ames Pretreatment Tower
1.72	19.7	1.34E-03	Ames Pretreatment Tower
1.72	17.2	7.33E-04	Ames Pretreatment Tower
1.66	19	1.01E-03	Ames Pretreatment Tower
1.64	14.8	1.36E-03	Ames Pretreatment Tower
1.79	11.7	9.39E-04	Ames Pretreatment Tower
1.81	14.9	1.69E-03	Ames Pretreatment Tower
1.78	17.6	1.47E-03	Ames Pretreatment Tower
1.77	18.8	1.35E-03	Ames Pretreatment Tower
1.75	14.2	1.29E-03	Ames Pretreatment Tower
1.75	11.9	1.25E-03	Ames Pretreatment Tower
1.76	11.7	1.38E-03	Ames Pretreatment Tower
0.249	17.3	7.47E-04	Huxley
0.401	9.8	3.45E-04	Huxley
0.34	10.1	4.20E-04	Midland, Mi
1.02	5.1	5.20E-04	Midland, Mi
1.02	6.6	6.20E-04	Midland, Mi
1.02	6.5	7.20E-04	Midland, Mi
1.02	6.5	5.00E-04	Midland, Mi
1.02	5.7	6.30E-04	Midland, Mi
0.679	12.1	9.60E-04	Midland, Mi
0.679	13	8.40E-04	Midland, Mi
0.679	17.6	1.03E-03	Midland, Mi
0.679	15.6	1.01E-03	Midland, Mi
1.36	13.1	1.36E-03	Midland, Mi
1.41	11.5	1.32E-03	Midland, Mi
1.07	11.3	1.26E-03	Midland, Mi
1.02	12.2	1.02E-03	Midland, Mi

Table B1. (Continued)

Hydraulic Load, L/m^2/s	Influent Ammonia, mgN/L	Ammonia Removal kgN/m^2/day, 10°C	source
0.822	9.9	9.90E-04	Midland, Mi
0.822	5.1	4.00E-04	Midland, Mi
4.82	7.5	5.00E-04	Midland, Mi
4.82	8.1	4.90E-04	Midland, Mi
4.82	11.7	6.40E-04	Midland, Mi
4.82	12.5	6.30E-04	Midland, Mi
0.767	5.4	3.60E-04	Bloom Township, Il
0.767	6.8	4.60E-04	Bloom Township, Il
0.767	7.3	4.80E-04	Bloom Township, Il
0.767	7.6	5.40E-04	Bloom Township, Il
0.767	6.4	4.50E-04	Bloom Township, Il
0.373	12.1	3.80E-04	Bloom Township, Il
0.373	16.3	4.90E-04	Bloom Township, Il
0.373	12.6	3.70E-04	Bloom Township, Il
1.66	7.3	7.50E-04	Bloom Township, Il
1.66	11.2	9.70E-04	Bloom Township, Il
1.66	10.9	9.90E-04	Bloom Township, Il
1.66	8.4	9.80E-04	Bloom Township, Il
1.66	8.8	1.08E-03	Bloom Township, Il
1.66	8.2	7.60E-04	Bloom Township, Il
1.66	10.5	1.14E-03	Bloom Township, Il
1.66	10.3	6.20E-04	Bloom Township, Il
2.78	8.5	1.04E-03	Bloom Township, Il
2.78	8	8.50E-04	Bloom Township, Il
2.78	12.1	1.06E-03	Bloom Township, Il
2.78	7.7	1.36E-03	Bloom Township, Il
1.23	4.8	7.00E-04	Bloom Township, Il
1.46	5.3	7.80E-04	Bloom Township, Il
1.46	5.6	7.70E-04	Bloom Township, Il
1.46	6.9	9.40E-04	Bloom Township, Il
1.46	7.9	9.50E-04	Bloom Township, Il
1.46	7.3	9.30E-04	Bloom Township, Il
1.46	5.3	6.80E-04	Bloom Township, Il
1.46	8.5	8.20E-04	Bloom Township, Il
1.46	9.1	7.10E-04	Bloom Township, Il
1.7	5	6.10E-04	Bloom Township, Il
1.7	5.1	8.40E-04	Bloom Township, Il
1.7	6	8.60E-04	Bloom Township, Il
1.7	5.7	9.10E-04	Bloom Township, Il
1.29	6.8	7.20E-04	Bloom Township, Il

Table B1. (Continued)

Hydraulic Load, L/m^2/s	Influent Ammonia, mgN/L	Ammonia Removal kgN/m^2/day, 10°C	source
1.29	4.8	7.70E-04	Bloom Township, Il
1.29	4.8	7.90E-04	Bloom Township, Il
1.29	5.3	7.90E-04	Bloom Township, Il
1.29	5.1	8.60E-04	Bloom Township, Il
1.29	4.9	8.40E-04	Bloom Township, Il
0.81	7.8	8.20E-04	Bloom Township, Il
0.81	7.8	8.40E-04	Bloom Township, Il
0.61	4.8	3.50E-04	Bloom Township, Il
0.75	6.4	5.60E-04	Bloom Township, Il
0.81	5.9	6.20E-04	Bloom Township, Il
0.81	5.6	6.10E-04	Bloom Township, Il
0.81	5.9	6.90E-04	Bloom Township, Il
0.81	5.9	6.80E-04	Bloom Township, Il
0.81	6.7	7.20E-04	Bloom Township, Il
0.394	18.5	2.19E-04	Parker & Richards
0.394	16.7	6.30E-04	Parker & Richards
0.767	10	1.03E-03	Parker & Richards
0.482	8.6	2.57E-04	Parker & Richards
0.475	9.6	2.45E-04	Parker & Richards
0.472	11.8	2.47E-04	Parker & Richards
0.472	11.8	1.63E-04	Parker & Richards
1	10.5	1.21E-04	Parker & Richards
0.389	11.4	2.00E-04	Parker & Richards
0.25	11.8	2.28E-04	Parker & Richards
0.25	11.8	3.19E-04	Parker & Richards
0.972	8.1	1.14E-04	Parker & Richards
0.667	12	2.22E-04	Parker & Richards
0.25	8.6	3.12E-04	Parker & Richards
0.679	5.5	1.44E-04	Sampayo
0.679	3.2	2.31E-04	Sampayo
0.679	5.5	4.53E-04	Sampayo
0.679	6.7	5.55E-04	Sampayo
0.679	7.2	6.06E-04	Sampayo
0.679	6.7	2.86E-04	Sampayo
0.679	7.3	3.61E-04	Sampayo
0.679	4.1	1.77E-04	Sampayo
1.359	5	1.71E-04	Sampayo
1.359	5.6	4.04E-04	Sampayo
1.359	6	4.21E-04	Sampayo
1.359	5.1	4.49E-04	Sampayo

Table B1. (Continued)

Hydraulic Load, L/m^2/s	Influent Ammonia, mgN/L	Ammonia Removal kgN/m^2/day, 10°C	source
1.359	5.6	4.83E-04	Sampayo
1.359	6.2	5.20E-04	Sampayo
1.359	5.8	4.46E-04	Sampayo
1.359	6.1	3.79E-04	Sampayo
1.359	5.4	3.89E-04	Sampayo
1.359	9.6	5.23E-04	Sampayo
1.359	11.5	9.38E-04	Sampayo
1.359	7.9	6.31E-04	Sampayo
1.359	10.4	9.06E-04	Sampayo
1.359	6.2	5.25E-04	Sampayo
1.359	4.8	4.28E-04	Sampayo
1.359	4.2	2.27E-04	Sampayo
1.359	6.6	4.01E-04	Sampayo

Table B2. Operating data set.

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.55	17	1.13E-04	AWPCF Stage 1 TFs
0.54	17	1.05E-04	AWPCF Stage 1 TFs
0.50	17	9.63E-05	AWPCF Stage 1 TFs
0.54	19	1.13E-04	AWPCF Stage 1 TFs
0.55	16	1.07E-04	AWPCF Stage 1 TFs
0.55	19	1.64E-04	AWPCF Stage 1 TFs
0.55	16	1.42E-04	AWPCF Stage 1 TFs
0.50	17	7.91E-05	AWPCF Stage 1 TFs
0.50	14	7.78E-05	AWPCF Stage 1 TFs
0.55	19	1.62E-04	AWPCF Stage 1 TFs
0.55	17	1.47E-04	AWPCF Stage 1 TFs
0.55	15	1.32E-04	AWPCF Stage 1 TFs
0.50	19	1.10E-04	AWPCF Stage 1 TFs
0.50	16	9.34E-05	AWPCF Stage 1 TFs
0.54	17	1.01E-04	AWPCF Stage 1 TFs
0.53	17	1.43E-04	AWPCF Stage 1 TFs
0.55	16	1.13E-04	AWPCF Stage 1 TFs
0.55	14	1.15E-04	AWPCF Stage 1 TFs
0.54	14	1.11E-04	AWPCF Stage 1 TFs
0.58	14	9.20E-05	AWPCF Stage 1 TFs
0.50	14	7.54E-05	AWPCF Stage 1 TFs
0.55	16	8.64E-05	AWPCF Stage 1 TFs
0.51	11	5.44E-05	AWPCF Stage 1 TFs
0.54	18	1.21E-04	AWPCF Stage 1 TFs
0.54	16	1.11E-04	AWPCF Stage 1 TFs
0.93	11	1.06E-04	AWPCF Stage 1 TFs
0.53	10	7.28E-05	AWPCF Stage 1 TFs
0.64	18	8.89E-05	AWPCF Stage 1 TFs
0.68	18	1.08E-04	AWPCF Stage 1 TFs
0.62	29	1.80E-04	AWPCF Stage 1 TFs
0.55	19	1.34E-04	AWPCF Stage 1 TFs
0.62	19	1.22E-04	AWPCF Stage 1 TFs
0.56	16	9.23E-05	AWPCF Stage 1 TFs
0.51	17	8.26E-05	AWPCF Stage 1 TFs
0.52	14	6.87E-05	AWPCF Stage 1 TFs
0.55	9.9	4.64E-05	AWPCF Stage 1 TFs
0.55	9	4.43E-05	AWPCF Stage 1 TFs
0.54	15	9.77E-05	AWPCF Stage 1 TFs
0.55	12	6.62E-05	AWPCF Stage 1 TFs
0.55	13	6.77E-05	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.55	9.6	4.62E-05	AWPCF Stage 1 TFs
0.52	12	4.21E-05	AWPCF Stage 1 TFs
0.50	11	4.78E-05	AWPCF Stage 1 TFs
0.55	14	5.58E-05	AWPCF Stage 1 TFs
0.55	13	5.34E-05	AWPCF Stage 1 TFs
0.55	18	8.97E-05	AWPCF Stage 1 TFs
0.54	13	6.96E-05	AWPCF Stage 1 TFs
0.55	14	5.90E-05	AWPCF Stage 1 TFs
0.53	14	5.46E-05	AWPCF Stage 1 TFs
0.55	13	5.74E-05	AWPCF Stage 1 TFs
0.54	11	4.78E-05	AWPCF Stage 1 TFs
0.55	23	8.26E-05	AWPCF Stage 1 TFs
0.54	16	8.22E-05	AWPCF Stage 1 TFs
0.50	13	3.89E-05	AWPCF Stage 1 TFs
0.50	10	3.72E-05	AWPCF Stage 1 TFs
0.55	12	5.25E-05	AWPCF Stage 1 TFs
0.55	9.5	3.41E-05	AWPCF Stage 1 TFs
0.55	10	3.58E-05	AWPCF Stage 1 TFs
0.55	12	5.87E-05	AWPCF Stage 1 TFs
0.50	13	6.02E-05	AWPCF Stage 1 TFs
0.55	14	6.58E-05	AWPCF Stage 1 TFs
0.51	18	5.65E-05	AWPCF Stage 1 TFs
0.51	15	4.64E-05	AWPCF Stage 1 TFs
0.51	17	5.49E-05	AWPCF Stage 1 TFs
0.54	17	4.58E-05	AWPCF Stage 1 TFs
0.54	16	4.07E-05	AWPCF Stage 1 TFs
0.55	20	3.80E-05	AWPCF Stage 1 TFs
0.54	20	5.58E-05	AWPCF Stage 1 TFs
0.55	15	5.39E-05	AWPCF Stage 1 TFs
0.54	21	5.07E-05	AWPCF Stage 1 TFs
0.61	20	2.79E-05	AWPCF Stage 1 TFs
0.67	20	4.76E-05	AWPCF Stage 1 TFs
0.59	18	4.10E-05	AWPCF Stage 1 TFs
0.55	15	3.47E-05	AWPCF Stage 1 TFs
0.54	16	6.71E-06	AWPCF Stage 1 TFs
0.62	18	5.80E-05	AWPCF Stage 1 TFs
0.55	23	7.12E-05	AWPCF Stage 1 TFs
0.54	24	8.10E-05	AWPCF Stage 1 TFs
0.55	22	7.36E-05	AWPCF Stage 1 TFs
0.60	17	5.36E-05	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.50	19	4.49E-05	AWPCF Stage 1 TFs
0.54	19	6.44E-05	AWPCF Stage 1 TFs
0.55	21	6.02E-05	AWPCF Stage 1 TFs
0.55	23	7.97E-05	AWPCF Stage 1 TFs
0.51	24	6.91E-05	AWPCF Stage 1 TFs
0.54	27	9.26E-05	AWPCF Stage 1 TFs
0.54	22	6.14E-05	AWPCF Stage 1 TFs
0.55	22	7.09E-05	AWPCF Stage 1 TFs
0.51	20	5.16E-05	AWPCF Stage 1 TFs
0.50	19	5.92E-05	AWPCF Stage 1 TFs
0.50	17	5.41E-05	AWPCF Stage 1 TFs
0.55	17	6.39E-05	AWPCF Stage 1 TFs
0.57	14	6.18E-05	AWPCF Stage 1 TFs
0.55	18	9.02E-05	AWPCF Stage 1 TFs
0.55	18	8.90E-05	AWPCF Stage 1 TFs
0.52	19	8.34E-05	AWPCF Stage 1 TFs
0.54	18	8.31E-05	AWPCF Stage 1 TFs
0.53	17	6.26E-05	AWPCF Stage 1 TFs
0.55	18	7.31E-05	AWPCF Stage 1 TFs
0.53	15	5.91E-05	AWPCF Stage 1 TFs
0.53	17	9.05E-05	AWPCF Stage 1 TFs
0.53	13	7.26E-05	AWPCF Stage 1 TFs
0.54	11	6.57E-05	AWPCF Stage 1 TFs
0.54	20	8.71E-05	AWPCF Stage 1 TFs
0.54	17	7.65E-05	AWPCF Stage 1 TFs
0.53	20	1.03E-04	AWPCF Stage 1 TFs
0.55	16	1.05E-04	AWPCF Stage 1 TFs
0.53	18	9.19E-05	AWPCF Stage 1 TFs
0.50	19	7.57E-05	AWPCF Stage 1 TFs
0.49	19	8.57E-05	AWPCF Stage 1 TFs
0.49	19	7.51E-05	AWPCF Stage 1 TFs
0.54	18	8.56E-05	AWPCF Stage 1 TFs
0.54	16	8.08E-05	AWPCF Stage 1 TFs
0.54	17	8.11E-05	AWPCF Stage 1 TFs
0.53	20	1.13E-04	AWPCF Stage 1 TFs
0.53	14	9.76E-05	AWPCF Stage 1 TFs
0.53	11	8.17E-05	AWPCF Stage 1 TFs
0.50	15	8.36E-05	AWPCF Stage 1 TFs
0.50	14	8.12E-05	AWPCF Stage 1 TFs
0.49	17	9.97E-05	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.53	17	8.24E-05	AWPCF Stage 1 TFs
0.52	18	9.24E-05	AWPCF Stage 1 TFs
0.40	16	7.94E-05	AWPCF Stage 1 TFs
0.53	22	1.27E-04	AWPCF Stage 1 TFs
0.52	19	1.12E-04	AWPCF Stage 1 TFs
0.52	19	9.56E-05	AWPCF Stage 1 TFs
0.52	22	1.18E-04	AWPCF Stage 1 TFs
0.50	22	1.19E-04	AWPCF Stage 1 TFs
0.54	18	1.09E-04	AWPCF Stage 1 TFs
0.51	26	8.93E-05	AWPCF Stage 1 TFs
0.44	18	6.97E-05	AWPCF Stage 1 TFs
0.44	17	6.66E-05	AWPCF Stage 1 TFs
0.47	14	5.62E-05	AWPCF Stage 1 TFs
0.45	17	8.48E-05	AWPCF Stage 1 TFs
0.52	21	1.16E-04	AWPCF Stage 1 TFs
0.55	21	1.20E-04	AWPCF Stage 1 TFs
0.51	22	1.16E-04	AWPCF Stage 1 TFs
0.50	22	1.19E-04	AWPCF Stage 1 TFs
0.52	18	9.19E-05	AWPCF Stage 1 TFs
0.52	18	8.90E-05	AWPCF Stage 1 TFs
0.52	20	9.71E-05	AWPCF Stage 1 TFs
0.53	16	8.56E-05	AWPCF Stage 1 TFs
0.46	17	7.59E-05	AWPCF Stage 1 TFs
0.39	19	7.52E-05	AWPCF Stage 1 TFs
0.55	22	1.41E-04	AWPCF Stage 1 TFs
0.48	21	1.17E-04	AWPCF Stage 1 TFs
0.61	18	1.15E-04	AWPCF Stage 1 TFs
0.51	19	1.25E-04	AWPCF Stage 1 TFs
0.50	23	1.17E-04	AWPCF Stage 1 TFs
0.57	22	1.10E-04	AWPCF Stage 1 TFs
0.52	18	9.08E-05	AWPCF Stage 1 TFs
0.54	14	8.39E-05	AWPCF Stage 1 TFs
0.57	13	6.49E-05	AWPCF Stage 1 TFs
0.54	14	6.80E-05	AWPCF Stage 1 TFs
0.46	15	6.56E-05	AWPCF Stage 1 TFs
0.47	14	6.36E-05	AWPCF Stage 1 TFs
0.45	17	7.45E-05	AWPCF Stage 1 TFs
0.53	23	1.49E-04	AWPCF Stage 1 TFs
0.55	23	1.60E-04	AWPCF Stage 1 TFs
0.53	23	1.55E-04	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.53	20	1.43E-04	AWPCF Stage 1 TFs
0.54	20	1.13E-04	AWPCF Stage 1 TFs
0.52	15	8.56E-05	AWPCF Stage 1 TFs
0.65	15	8.93E-05	AWPCF Stage 1 TFs
0.61	15	8.61E-05	AWPCF Stage 1 TFs
0.57	18	9.23E-05	AWPCF Stage 1 TFs
0.58	17	9.57E-05	AWPCF Stage 1 TFs
0.53	17	7.81E-05	AWPCF Stage 1 TFs
0.86	13	9.07E-05	AWPCF Stage 1 TFs
0.71	14	1.16E-04	AWPCF Stage 1 TFs
0.67	15	1.20E-04	AWPCF Stage 1 TFs
0.63	15	1.14E-04	AWPCF Stage 1 TFs
0.92	13	1.43E-04	AWPCF Stage 1 TFs
0.84	10	8.16E-05	AWPCF Stage 1 TFs
0.82	10	7.72E-05	AWPCF Stage 1 TFs
0.84	11	8.99E-05	AWPCF Stage 1 TFs
0.94	8.5	7.93E-05	AWPCF Stage 1 TFs
0.80	12	1.05E-04	AWPCF Stage 1 TFs
0.81	12	1.10E-04	AWPCF Stage 1 TFs
0.79	13	1.14E-04	AWPCF Stage 1 TFs
0.78	13	1.12E-04	AWPCF Stage 1 TFs
0.61	11	6.46E-05	AWPCF Stage 1 TFs
0.74	11	8.25E-05	AWPCF Stage 1 TFs
0.62	16	1.01E-04	AWPCF Stage 1 TFs
0.47	16	5.50E-05	AWPCF Stage 1 TFs
1.05	7.9	1.02E-04	AWPCF Stage 1 TFs
0.74	9.4	7.94E-05	AWPCF Stage 1 TFs
0.83	11	1.19E-04	AWPCF Stage 1 TFs
1.04	8.8	1.20E-04	AWPCF Stage 1 TFs
0.90	9.9	1.14E-04	AWPCF Stage 1 TFs
0.85	8	7.32E-05	AWPCF Stage 1 TFs
0.54	10	5.44E-05	AWPCF Stage 1 TFs
0.59	9.2	5.49E-05	AWPCF Stage 1 TFs
0.74	8.4	6.02E-05	AWPCF Stage 1 TFs
0.52	12	6.92E-05	AWPCF Stage 1 TFs
0.61	12	9.15E-05	AWPCF Stage 1 TFs
0.93	7.4	8.23E-05	AWPCF Stage 1 TFs
0.80	6.4	6.22E-05	AWPCF Stage 1 TFs
0.86	7.5	6.25E-05	AWPCF Stage 1 TFs
0.83	7.2	5.52E-05	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.81	8.8	6.78E-05	AWPCF Stage 1 TFs
0.78	9.2	7.23E-05	AWPCF Stage 1 TFs
0.66	8.7	4.81E-05	AWPCF Stage 1 TFs
0.57	13	7.91E-05	AWPCF Stage 1 TFs
0.53	13	7.18E-05	AWPCF Stage 1 TFs
0.51	13	7.02E-05	AWPCF Stage 1 TFs
0.59	8.6	4.25E-05	AWPCF Stage 1 TFs
0.52	10	4.05E-05	AWPCF Stage 1 TFs
0.53	11	4.64E-05	AWPCF Stage 1 TFs
0.54	12	5.23E-05	AWPCF Stage 1 TFs
0.54	11	4.43E-05	AWPCF Stage 1 TFs
0.53	11	4.49E-05	AWPCF Stage 1 TFs
0.55	11	4.57E-05	AWPCF Stage 1 TFs
0.45	10	3.02E-05	AWPCF Stage 1 TFs
0.47	11	3.43E-05	AWPCF Stage 1 TFs
0.46	11	3.82E-05	AWPCF Stage 1 TFs
0.52	15	6.83E-05	AWPCF Stage 1 TFs
0.52	15	6.99E-05	AWPCF Stage 1 TFs
0.54	12	6.51E-05	AWPCF Stage 1 TFs
0.53	11	4.04E-05	AWPCF Stage 1 TFs
0.54	12	4.77E-05	AWPCF Stage 1 TFs
0.53	11	4.49E-05	AWPCF Stage 1 TFs
0.56	11	4.49E-05	AWPCF Stage 1 TFs
0.53	12	4.76E-05	AWPCF Stage 1 TFs
0.54	12	4.42E-05	AWPCF Stage 1 TFs
0.46	14	4.12E-05	AWPCF Stage 1 TFs
0.57	13	5.09E-05	AWPCF Stage 1 TFs
0.62	13	5.46E-05	AWPCF Stage 1 TFs
0.66	17	9.50E-05	AWPCF Stage 1 TFs
0.54	23	7.55E-05	AWPCF Stage 1 TFs
0.54	14	5.48E-05	AWPCF Stage 1 TFs
0.61	18	6.28E-05	AWPCF Stage 1 TFs
0.47	22	4.24E-05	AWPCF Stage 1 TFs
0.46	22	7.52E-05	AWPCF Stage 1 TFs
0.53	22	6.98E-05	AWPCF Stage 1 TFs
0.52	18	7.00E-05	AWPCF Stage 1 TFs
0.54	24	8.52E-05	AWPCF Stage 1 TFs
0.54	23	9.40E-05	AWPCF Stage 1 TFs
0.46	23	6.76E-05	AWPCF Stage 1 TFs
0.54	18	6.21E-05	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.53	19	7.89E-05	AWPCF Stage 1 TFs
0.53	23	8.85E-05	AWPCF Stage 1 TFs
0.52	20	8.64E-05	AWPCF Stage 1 TFs
0.47	28	8.30E-05	AWPCF Stage 1 TFs
0.46	22	7.85E-05	AWPCF Stage 1 TFs
0.50	25	1.13E-04	AWPCF Stage 1 TFs
0.46	20	9.86E-05	AWPCF Stage 1 TFs
0.52	17	7.91E-05	AWPCF Stage 1 TFs
0.46	20	7.78E-05	AWPCF Stage 1 TFs
0.47	22	9.75E-05	AWPCF Stage 1 TFs
0.51	21	1.08E-04	AWPCF Stage 1 TFs
0.52	21	9.73E-05	AWPCF Stage 1 TFs
0.46	17	7.99E-05	AWPCF Stage 1 TFs
0.49	15	8.90E-05	AWPCF Stage 1 TFs
0.52	14	8.49E-05	AWPCF Stage 1 TFs
0.52	19	1.24E-04	AWPCF Stage 1 TFs
0.50	22	1.25E-04	AWPCF Stage 1 TFs
0.52	18	1.11E-04	AWPCF Stage 1 TFs
0.51	24	1.34E-04	AWPCF Stage 1 TFs
0.51	27	1.32E-04	AWPCF Stage 1 TFs
0.52	22	1.01E-04	AWPCF Stage 1 TFs
0.51	22	1.21E-04	AWPCF Stage 1 TFs
0.51	24	1.27E-04	AWPCF Stage 1 TFs
0.55	25	1.33E-04	AWPCF Stage 1 TFs
0.52	22	9.89E-05	AWPCF Stage 1 TFs
0.51	21	1.13E-04	AWPCF Stage 1 TFs
0.52	21	1.17E-04	AWPCF Stage 1 TFs
0.52	20	1.27E-04	AWPCF Stage 1 TFs
0.52	18	1.21E-04	AWPCF Stage 1 TFs
0.52	15	9.58E-05	AWPCF Stage 1 TFs
0.51	17	9.63E-05	AWPCF Stage 1 TFs
0.52	12	9.28E-05	AWPCF Stage 1 TFs
0.51	14	1.07E-04	AWPCF Stage 1 TFs
0.51	15	1.17E-04	AWPCF Stage 1 TFs
0.50	15	1.13E-04	AWPCF Stage 1 TFs
0.49	21	1.38E-04	AWPCF Stage 1 TFs
0.52	21	1.40E-04	AWPCF Stage 1 TFs
0.51	17	1.16E-04	AWPCF Stage 1 TFs
0.51	21	1.36E-04	AWPCF Stage 1 TFs
0.52	13	6.97E-05	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.51	16	8.43E-05	AWPCF Stage 1 TFs
0.57	20	1.33E-04	AWPCF Stage 1 TFs
0.51	19	1.25E-04	AWPCF Stage 1 TFs
0.51	18	1.07E-04	AWPCF Stage 1 TFs
0.52	16	7.57E-05	AWPCF Stage 1 TFs
0.52	18	8.81E-05	AWPCF Stage 1 TFs
0.52	18	8.57E-05	AWPCF Stage 1 TFs
0.53	19	7.64E-05	AWPCF Stage 1 TFs
0.51	14	7.84E-05	AWPCF Stage 1 TFs
0.51	21	9.61E-05	AWPCF Stage 1 TFs
0.50	22	9.49E-05	AWPCF Stage 1 TFs
0.44	18	7.09E-05	AWPCF Stage 1 TFs
0.50	18	7.36E-05	AWPCF Stage 1 TFs
0.52	21	9.35E-05	AWPCF Stage 1 TFs
0.54	11	3.92E-05	AWPCF Stage 1 TFs
0.56	18	6.92E-05	AWPCF Stage 1 TFs
0.57	15	6.37E-05	AWPCF Stage 1 TFs
0.55	15	6.08E-05	AWPCF Stage 1 TFs
0.56	15	4.80E-05	AWPCF Stage 1 TFs
0.55	16	4.69E-05	AWPCF Stage 1 TFs
0.61	11	3.44E-05	AWPCF Stage 1 TFs
0.55	19	5.32E-05	AWPCF Stage 1 TFs
0.54	18	5.37E-05	AWPCF Stage 1 TFs
0.62	18	6.13E-05	AWPCF Stage 1 TFs
0.61	18	6.50E-05	AWPCF Stage 1 TFs
0.55	19	6.16E-05	AWPCF Stage 1 TFs
0.55	20	6.18E-05	AWPCF Stage 1 TFs
0.53	20	6.53E-05	AWPCF Stage 1 TFs
0.52	12	4.96E-05	AWPCF Stage 1 TFs
0.61	13	5.61E-05	AWPCF Stage 1 TFs
0.56	12	5.37E-05	AWPCF Stage 1 TFs
0.55	12	5.91E-05	AWPCF Stage 1 TFs
0.55	14	5.78E-05	AWPCF Stage 1 TFs
0.55	15	6.86E-05	AWPCF Stage 1 TFs
0.56	13	5.58E-05	AWPCF Stage 1 TFs
0.54	18	7.33E-05	AWPCF Stage 1 TFs
0.53	14	5.98E-05	AWPCF Stage 1 TFs
0.52	16	5.90E-05	AWPCF Stage 1 TFs
0.56	17	5.09E-05	AWPCF Stage 1 TFs
0.55	16	5.18E-05	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.55	16	5.15E-05	AWPCF Stage 1 TFs
0.55	18	5.74E-05	AWPCF Stage 1 TFs
0.56	21	7.28E-05	AWPCF Stage 1 TFs
0.56	16	5.60E-05	AWPCF Stage 1 TFs
0.55	14	5.76E-05	AWPCF Stage 1 TFs
0.53	11	4.74E-05	AWPCF Stage 1 TFs
0.52	14	5.70E-05	AWPCF Stage 1 TFs
0.55	12	4.07E-05	AWPCF Stage 1 TFs
0.55	11	4.72E-05	AWPCF Stage 1 TFs
0.55	12	4.79E-05	AWPCF Stage 1 TFs
0.52	13	4.80E-05	AWPCF Stage 1 TFs
0.52	12	5.05E-05	AWPCF Stage 1 TFs
0.52	12	4.74E-05	AWPCF Stage 1 TFs
0.55	11	4.20E-05	AWPCF Stage 1 TFs
0.55	16	1.38E-05	AWPCF Stage 1 TFs
0.55	18	6.76E-05	AWPCF Stage 1 TFs
0.55	17	6.21E-05	AWPCF Stage 1 TFs
0.52	18	5.54E-05	AWPCF Stage 1 TFs
0.52	16	6.81E-05	AWPCF Stage 1 TFs
0.54	15	5.12E-05	AWPCF Stage 1 TFs
0.55	17	6.06E-05	AWPCF Stage 1 TFs
0.55	17	6.12E-05	AWPCF Stage 1 TFs
0.54	18	6.49E-05	AWPCF Stage 1 TFs
0.52	17	5.95E-05	AWPCF Stage 1 TFs
0.52	20	7.67E-05	AWPCF Stage 1 TFs
0.52	18	6.70E-05	AWPCF Stage 1 TFs
0.55	17	6.78E-05	AWPCF Stage 1 TFs
0.54	17	6.80E-05	AWPCF Stage 1 TFs
0.55	18	6.57E-05	AWPCF Stage 1 TFs
0.52	18	5.87E-05	AWPCF Stage 1 TFs
0.52	18	5.93E-05	AWPCF Stage 1 TFs
0.55	17	6.34E-05	AWPCF Stage 1 TFs
0.55	18	7.05E-05	AWPCF Stage 1 TFs
0.55	21	8.38E-05	AWPCF Stage 1 TFs
0.55	22	5.72E-05	AWPCF Stage 1 TFs
0.56	36	9.15E-05	AWPCF Stage 1 TFs
0.54	18	8.25E-05	AWPCF Stage 1 TFs
0.54	19	8.22E-05	AWPCF Stage 1 TFs
0.52	19	8.25E-05	AWPCF Stage 1 TFs
0.55	18	7.20E-05	AWPCF Stage 1 TFs

Table B2. (Continued)

Hydraulic loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbs/ft^2/day	Source
0.54	17	1.06E-04	AWPCF Stage 1 TFs
0.56	13	1.62E-05	AWPCF Stage 1 TFs
0.51	19	7.63E-05	AWPCF Stage 1 TFs
0.50	17	8.06E-05	AWPCF Stage 1 TFs
0.55	19	8.16E-05	AWPCF Stage 1 TFs
0.54	16	8.33E-05	AWPCF Stage 1 TFs
0.54	13	7.68E-05	AWPCF Stage 1 TFs

Table B3. Experimental data set.

Hydraulic Loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbsN/ft^2/day	Source AWPCF TF #
0.80	1.00	6.26E-06	3
0.79	1.29	7.42E-06	3
0.79	0.69	4.10E-06	3
0.79	0.89	3.64E-06	3
0.79	0.91	3.99E-06	3
1.27	0.32	2.36E-06	4
1.27	0.10	5.65E-07	4
1.27	<.1	0.00E+00	4
1.59	0.69	7.40E-06	4
1.60	0.93	1.02E-05	4
1.44	0.84	8.00E-06	4
1.62	1.05	1.21E-05	4
1.61	1.32	1.40E-05	4
1.61	0.55	5.59E-06	4
1.60	0.96	9.63E-06	4
1.59	1.05	1.11E-05	4
1.61	1.24	1.47E-05	4
1.61	0.99	1.09E-05	4
1.62	1.43	2.52E-05	4
0.79	1.16	6.37E-06	3
0.79	1.00	5.62E-06	3
0.80	1.46	9.01E-06	3
0.68	23.88	1.73E-04	1
0.42	20.36	1.06E-04	2
0.78	0.93	4.09E-06	3
1.59	0.89	8.20E-06	4
0.66	23.37	1.66E-04	1
0.40	21.25	1.11E-04	2
0.79	0.80	3.15E-06	3
1.60	0.72	7.39E-06	4
0.61	17.22	1.03E-04	1
0.37	18.30	9.70E-05	2
0.78	1.41	8.22E-06	3
1.59	1.28	1.61E-05	4
0.61	18.38	1.23E-04	1
0.37	18.38	8.95E-05	2
0.79	1.08	6.11E-06	3
1.60	1.12	1.42E-05	4
0.62	11.33	8.13E-05	1
0.38	11.53	5.80E-05	2
0.79	0.28	1.27E-06	3

Table B3. (Continued)

Hydraulic Loading, gpm/ft2	Applied NH3, mgN/L	Adjusted specific removal, 10°C basis, lbsN/ft^2/day	Source AWPCF TF #
1.59	0.14	4.99E-08	4
0.59	22.41	1.51E-04	1
0.36	20.00	9.12E-05	2
1.27	1.27	1.11E-05	3
1.12	1.05	9.27E-06	4
0.66	20.99	1.66E-04	1
0.40	20.00	1.09E-04	2
1.28	1.20	1.06E-05	3
1.14	1.15	1.04E-05	4
0.56	23.61	1.55E-04	1
0.50	23.61	1.35E-04	2
1.28	0.93	6.34E-06	3
1.13	0.90	7.41E-06	4
0.65	20.85	1.66E-04	1
0.40	19.05	9.68E-05	2
0.80	0.52	2.93E-06	3
1.62	0.39	4.69E-06	4
0.65	23.80	1.55E-04	1
0.40	23.26	1.07E-04	2
0.78	0.83	4.80E-06	3
1.59	0.69	8.39E-06	4
0.67	20.01	1.55E-04	1
0.41	19.83	1.11E-04	2
0.77	0.85	5.32E-06	3
1.57	0.71	9.04E-06	4
0.63	12.74	8.63E-05	1
0.39	9.84	5.09E-05	2
0.79	0.36	2.19E-06	3
1.61	0.23	3.05E-06	4
0.64	10.11	2.94E-04	1
0.39	8.79	1.60E-04	2
0.79	0.24	4.47E-06	3
1.60	0.05	1.34E-06	4
0.69	6.61	6.69E-05	1
0.42	6.13	3.91E-05	2
0.77	0.21	1.33E-06	3
1.57	0.03	2.44E-07	4

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ACKNOWLEDGEMENTS