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Nitrogen removal from wastewater by an aerated subsurface flow constructed wetland

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NITROGEN REMOVAL FROM WASTEWATER BY AN AERATED SUBSURFACE FLOW CONSTRUCTED WETLAND

by

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Eric Redmond

has been approved by the Examining Committee for the
thesis requirement for the Master of Science degree in
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To my Grandpa Jim, who was always giving support and looking on the bright side.

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ABSTRACT

The purpose of this research was to assess the ability of subsurface flow wetlands, with aeration and vegetation, to remove nitrogen in cold weather climates. Aeration was shown to enhance the wetland cell's ability to remove not only nitrogen but also CBOD, COD, and phosphorus (retention) more effectively. There was a significant difference ($p< 0.05$) in both total nitrogen and ammonia effluent concentrations comparing aerated to unaerated wetland cells, while no significance was found comparing planted and unplanted wetland cells.

The effluent ammonia concentrations from the aerated wetland cells ranged from 2.7 to 5.7 mg N/L, while for unaerated cells effluent concentration ranged from 22 to 23 mg N/L. The effluent total nitrogen concentrations from the aerated wetland cells ranged from 9.0 to 12 mg N/L, while those from unaerated cells ranged from 23 to 24 mg N/L. The effluent concentrations showed no significant difference ($p < 0.05$) when comparing results of three temperature ranges. There is a correlation when comparing ammonia mass removal rates to mass loading rates. Ammonia removal in the aerated wetland cells ranged from 82 to 95%, while unaerated cells ranged from 39 to 45%.

The hydraulic retention times ranged from 3.13 to 4.33 days and the tanks-in-series ranged from 1.46 to 2.84. Using this information the wetland cells were modeled using both the TIS and the PkC* models. The k values (PkC* model) of the aerated wetlands for ammonia ranged from 131 to 221 m/d, while the unaerated wetland cells had values ranging from 20.4 to 36.7 m/d. The models appear to show a good prediction of the effluent ammonia concentration for the unaerated cells but the aerated cells show the model does not effectively capture the effects of aeration.

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CHAPTER 1

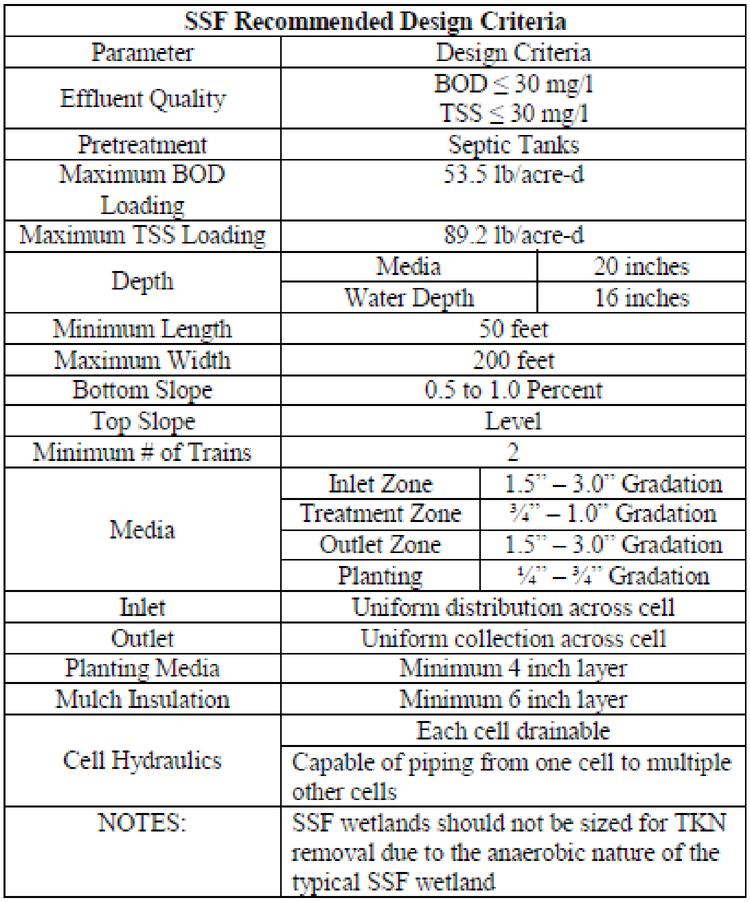
INTRODUCTION

“The concept of decentralized wastewater management arises from a realization that conventional, large-scale treatment works cannot cost-effectively solve the wastewater management issues in areas with low population density (Wallace and Knight, 2006).” This rings particularly true when considering options for wastewater management within Iowa’s rural communities, classified as populations from 25-250. The state of Iowa has provided guidelines for five alternative technologies that include: recirculating media filters, sand mounds, drip dispersal, constructed wetlands, and alternative collections systems (Design Guidance IDNR, 2012). Updated guidelines were needed to assist communities with stricter NPDES Permit limits for bacteria and end-of-pipe ammonia limits. Table 1 provides the design guidelines for the installing of constructed wetlands, specifically subsurface flow (SSF) wetlands (Design Guidance IDNR, 2012).

These design criteria show that constructed SSF wetlands should not be considered if ammonia removal is necessary (TKN = ammonia-N + organic-N). Wetland technology fits well into single family and medium density population areas that are required to meet stringent effluent requirements.

Wetlands are considered attached-growth biological filters that utilize vegetation for additional treatment advantages. They offer the advantage of appearing as natural wetlands and offer the habitat for a natural ecosystem. They are a viable option for low population areas because of the low economical, energy, and operator support input required. In colder climates surface flow wetlands are not considered a viable option for

Table 1. Iowa Department of Natural Resources Recommended Design Criteria for Subsurface Flow Wetlands.



SSF Recommended Design Criteria		
Parameter	Design Criteria	
Effluent Quality	BOD ≤ 30 mg/l TSS ≤ 30 mg/l	
Pretreatment	Septic Tanks	
Maximum BOD Loading	53.5 lb/acre-d	
Maximum TSS Loading	89.2 lb/acre-d	
Depth	Media	20 inches
	Water Depth	16 inches
Minimum Length	50 feet	
Maximum Width	200 feet	
Bottom Slope	0.5 to 1.0 Percent	
Top Slope	Level	
Minimum # of Trains	2	
Media	Inlet Zone	1.5" – 3.0" Gradation
	Treatment Zone	¾" – 1.0" Gradation
	Outlet Zone	1.5" – 3.0" Gradation
	Planting	¼" – ¾" Gradation
Inlet	Uniform distribution across cell	
Outlet	Uniform collection across cell	
Planting Media	Minimum 4 inch layer	
Mulch Insulation	Minimum 6 inch layer	
Cell Hydraulics	Each cell drainable	
	Capable of piping from one cell to multiple other cells	
NOTES:	SSF wetlands should not be sized for TKN removal due to the anaerobic nature of the typical SSF wetland	

cold temperature treatment because of the concern for freezing. SSF wetlands have overcome this barrier with an insulating layer to prevent freezing. This insulating layer not only prevents freezing but also limits human exposure to disease as well as not providing a suitable habitat for mosquitoes. The disadvantage compared to free surface wetlands is the limited amount of oxygen available. This is why The University of Iowa has constructed a unique pilot-scale wetland using SSF wetlands that are provided with aeration. The design of the aerated subsurface flow wetlands is based on previous designs and considerations from Scott Wallace, who holds the patent on aerated wetlands. The aeration will allow for nitrification to occur and during the anaerobic cycle denitrification can occur, effectively resulting in nitrogen removal. The set-up has duplicate wetlands of four different wetlands treatment schemes:

- Non-planted and non-aerated;
- Non-planted and aerated;
- Planted and non-aerated; and
- Planted and aerated.

This set-up will allow examination of the role vegetation and aeration have on the treatment of primary treated wastewater. The insulating layer of mulch will allow treatment to remain effective through Iowa's winter months. This technology has the ability to effectively transform ammonia nitrogen to nitrate and through alternating periods of aeration and no aeration, remove nitrate in the form ofnitrogen gas.

1.1 Research Objectives

The primary research objective of this study was to assess the ability of aeration within a wetland setting to enhance transformation and removal of nitrogen (NH_3, NO_2^-, NO_3^-, organic nitrogen, and total nitrogen). A secondary objective of the study was to assess the role of plants in transforming and removing nitrogen. A third objective was to develop design guidance for nitrogen removal by aerated wetlands. All three of these objectives also include the overall objective that cold weather nitrogen removal using aerated SSF wetlands is a feasible and viable technology. Specific research objectives include:

1. Assess nitrogen removal efficiency during winter months.
2. Assess nitrogen removal efficiency in regards to vegetation and aeration.
3. Identify and model the flow regime of the wetland;
4. Use the flow model for the wetland to identify a model adequate to model nitrogen removal.
5. Calculate reaction rate coefficients for nitrogen removal.
6. Monitor other pollutants of concern; namely BOD and COD, total suspended solids (TSS), and inorganic phosphorus.

CHAPTER 2
BACKGROUND AND LITERATURE REVIEW

2.1 Nitrogen Transformation and Removal Pathways

Nitrogen species are a major concern when treating wastewaters because of the toxicity (NH_3), oxygen demand (NH_3, Org-N), and potential for euthrophication (all forms). Common nitrogen forms in the influent of typical municipal wastewaters include: ammonia and organic nitrogen with little-to-no nitrate and nitrite. Figure 1 shows the nitrogen cycle within a wetland setting and shows how complex the nitrogen cycle can be. Not shown is the impact of aeration on the nitrogen cycle; and with the addition of aeration nitrification/denitrification becomes the dominant nitrogen removal mechanism. Nitrogen gas fixation and ammonia volatilization play a minimal role in SSF wetlands because the wastewater is not in direct contact with the atmosphere.

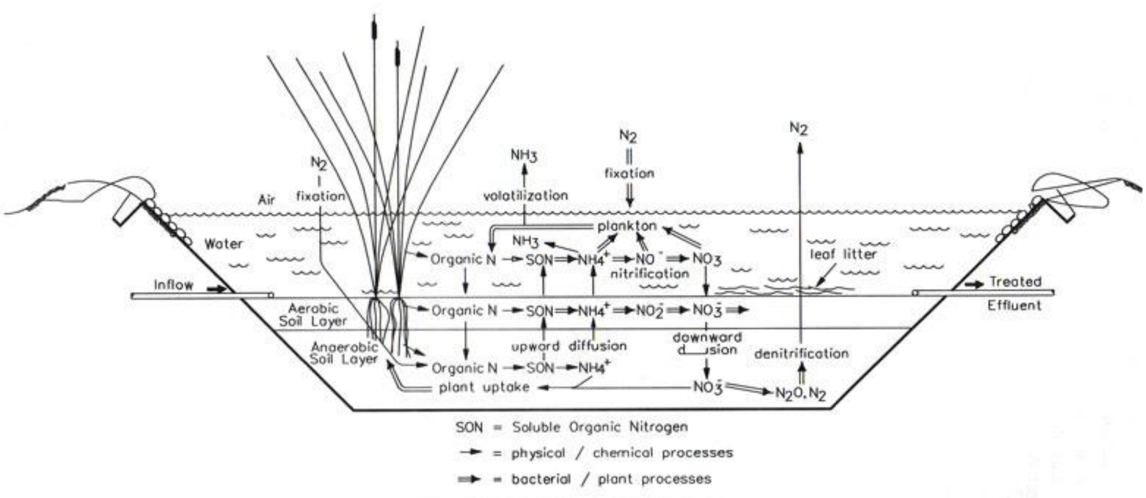


Figure 1. Nitrogen cycle in a free-water surface wetland (Figure: “Ecological Design” (*Gaia Education)*, 2012)

Nitrogen within a wetland is often cycled from organic to inorganic and vice versa. The transformations each have requirements for a reaction to take place; ammonia to nitrate is autotrophic and obtains energy from ammonia oxidation, while the conversion of nitrate to nitrogen gas is heterotrophic requiring organic carbon. The physical processes of nitrogen cycling are settling and resuspension, diffusion, plant translocation, litterfall, sorption and ammonia volatilization (Kadlec and Wallace, 2009). The five principal processes for nitrogen transformations in a submerged wetland are (Kadlec and Wallace, 2009):

- Ammonication;
- Nitrification;
- Denitrification;
- Assimilation; and
- Decomposition.

Nitrogen transformation reactions can be seen in Table 2. Biogeochemical transformation of nitrogen in wetlands (Vymazal, 2007).Ammonia typically has the highest concentration of the nitrogen forms in a domestic wastewater. Organic nitrogen can be transformed into ammonia nitrogen via ammonification. Organic nitrogen is included in total kjeldahl nitrogen (TKN) as a potential ammonia source. Ammonification can be carried out aerobically as well as anaerobically and is considered a relatively fast transformation (Kadlec and Wallace, 2009). Sorption of ammonia to media (inorganic) or mulch/soil (organic) is a physical ammonia removal mechanism. Once adsorbed it can either be transformed into nitrate via nitrification (if conditions allow) with the nitrate dissolving into the wastewater or ammonia can be released if the wastewater chemistry changes. It has been suggested that ammonia sorption can be a seasonal process whereby ammonia is stored for later release and use (Wittgren and Maehlum, 1997). The dominant form of ammonia transformation in the presence of oxygen is bacterial nitrification, resulting in either nitrite or nitrate depending on how complete the transformation is.

Table 2. Biogeochemical transformation of nitrogen in wetlands (Vymazal, 2007).

Process	**Transformation (not balanced)**
Volatilzation	$NH_{3(aq)} \rightarrow NH_{3\,(g)}$
Ammonification	$\text{Organic-N}_{(aq)} \rightarrow NH_{3\,(aq)}$
Nitritation	$2NH_4^+{}_{(aq)} + 3O_2 \rightarrow 2NO_2^-{}_{(aq)} + 2H_2O_{(aq)} + 4H^+{}_{(aq)}$
Nitrification	$2NO_2^-{}_{(aq)} + O_2 \rightarrow 2NO_3^-{}_{(aq)}$
Denitrification	$2NO_3^-{}_{(aq)} \rightarrow 2NO_2^-{}_{(aq)} \rightarrow 2NO_{(g)} \rightarrow N_2O_{(g)} \rightarrow N_{2\,(g)}$
Dissimilatory Nitrate Reduction	$2NO_3^-{}_{(aq)} \rightarrow NH_{3\,(aq)}$
N_2 Fixation	$N_{2\,(g)} \rightarrow \text{Organic-N}_{(aq)}, NH_{3\,(aq)}$
Biological Assimilation	$NH_{3\,(aq)}, NO_2^-{}_{(aq)}, NO_3^-{}_{(aq)} \rightarrow \text{Organic-N}_{(aq)}$
Ammonia Adsorption	$NH_{3\,(aq)} \rightarrow NH_{3\,(s)}$
ANAMMOX	$NH_{3\,(aq)} + NO_2^-{}_{(aq)} \rightarrow N_{2\,(g)}$

The first step in the transformation is nitritation, which requires 3.43 g O_2/g NH_3-N and the second step is nitrification, which requires 1.14 g O_2/g NH_3-N (Kadlec and

Wallace, 2009). If oxygen is not present within a wetland setting, ammonia oxidation is highly limited; however, laboratory studies have found that a wetland supplied with aeration can have a tenfold increase in nitrification rates (Kinsley *et al.*, 2002). Nitrification is carried out via autotrophic bacteria, while denitrification is carried out via facultative heterotrophic bacteria. Nitrification alone will not result in nitrogen removal, but when coupled with denitrification significant nitrogen removal is possible. Cycling aeration on and off throughout a treatment cycle allows for both types of bacteria to perform their respective transformations. Lack of carbon in wastewater can contribute to limited denitrification.

Vegetation can uptake nitrogen as well as provide a carbon source and attachment sites for microbial activity. Previously, the root zone of vegetation was thought to contribute oxygen to a subsurface flow wetland. However, it has recently been shown to be insignificant in terms of nitrogen transformations (Vymazal, 2007). If oxygen is limited in wetlands, but still present in high enough concentrations to allow nitritation to occur a phenomenon called ANAMMOX (Anaerobic Ammonia Oxidation) could cause nitrogen removal. The oxygen requirement for ANAMMOX to occur is 1.94 g O_2/g NH_3-N (Kadlec and Wallace, 2009).

Ammonia removal in subsurface flow wetlands has been shown to vary widely. One study using three planted and one unplanted subsurface flow wetlands for tertiary treatment showed ammonia reductions of 17-24% and 34%, respectively (Thomas, 1995). A study by Nivala *et al.* (2007) observed greater than 90% ammonia reduction throughout every season using an aerated subsurface flow wetland to treat landfill leachate. The lowest ammonia reductions were observed during the winter months but still exceeded 90% removal. Using the same wetland Nivala *et al.* (2007) observed ammonia reductions ranging from 14-40% when aeration was not provided.

One study using subsurface flow wetlands to observe total nitrogen (TN) removal in a cold climate (average temperature -7°C) had aeration provided for pretreatment and had removals of 48% (single wetland) and 59% (for two consecutive wetlands) (Maehlum, 1995). Another study comparing the results of 22 nonaerated and 17 aerated subsurface flow wetlands observed that 50% and 90% bounds for effluent TKN concentration were lower for the aerated wetlands (Wallace *et al.*, 2008). The difference was not as large or as significant as expected, and could be due to the fact that some wetlands had been retrofitted for aeration and might not have had a sufficient supply of oxygen (Wallace *et al.*, 2008). Subsurface flow wetlands treating septic tank effluent showed reduction of inorganic nitrogen influent concentrations of 6.7 and 9.4 mg/L to 1.2 and 4.2 mg/L in the effluent, respectively (Mander and Jenssen, 2003).

2.2 Organic Matter Removal

Organic compounds can be found in abundance in untreated wastewater causing it to be a main priority of treatment. Organic compounds undergo rapid utilization within wetland systems. The two tests most commonly used to measure the concentration of organic content are the carbonaceous biochemical oxygen demand (CBOD) and chemical oxygen demand (COD). CBOD is a measure of oxygen required for microbial oxidation of the organic matter. COD is a measure of the amount of chemical oxidant needed to oxidize the organic matter. Neither test measures the amount of oxygen required for nitrification. The COD test also measures non-biodegradable organics, resulting in the effluent with CBOD/COD values of 0.1-0.3 in the final effluent of conventional wastewater treatment (Tchobanoglous *et al.*, 2004).

Horizontal Sub-Surface Flow wetlands were once thought of as horizontal trickling filters in which biofilm attached to media is responsible for organic matter removal (Kadlec and Wallace, 2009). It has since been understood that there are more mechanisms working within a sub-surface wetland; primarily sedimentation, adsorption and microbial metabolism (Karathanasis *et al.*, 2003).

Microbial metabolism is significantly different when comparing an anaerobic system versus an aerobic system. HSS wetlands that are not provided aeration remove organic matter most by anaerobic processes. These processes include: fermentation and nitrate reduction (denitrification), and iron and sulfate reduction (Kadlec and Wallace, 2009). If aeration is provided heterotrophic oxidation of organic matter can occur and rates significantly increase (Kadlec and Wallace, 2009). A study comparing 22 nonaerated and 17 aerated SSF wetlands showed that aerated wetlands gave lower median effluent BOD concentrations (Wallace *et al.*, 2008). The study also reported that aerated wetlands experienced more consistent effluent BOD quality over nonaerated wetlands as loading increased (Wallace *et al.*, 2008). Removals of BOD by a planted aerated wetland were greater than 90% with a peak of 97% (Nivala *et al.*, 2007). With the same wetland without aeration, removals of BOD were from 75-81% (Nivala *et al.*, 2007).

Vegetation can provide additional oxygen through the root zone as well as increasing the surface available for bacteria. Plants also provide carbon to the system via decomposition. Tanner (2001) concluded that wetland plants provided only a small improvement in terms of BOD and COD removal. A study assessing twelve SSF wetlands treating single family home wastewater found that removal efficiency was significantly lower in unplanted wetlands versus planted wetlands (Karathanasis, 2003). Removal for unplanted wetlands was 63%, while for planted wetlands removals ranged from 75-79% (Karathanasis, 2003). The study considered it likely that plant roots and residue provided additional settling or filtration characteristics over unplanted wetlands (Karathanasis, 2003).

2.3 Total Suspended Solids Retention

One of the major functions of constructed wetlands treatment is solids removal. Solids are primarily removed by settling within a free surface wetland, but contributions from interception (passage blocking) both by bed material and plant debris, along with biofilm filtration become larger contributors for subsurface flow wetlands. Pollutants such as metals and organic materials can be attached to particles and will therefore become retained within the wetland system. One of the primary mechanisms for retention, settling, is effective because the settling distance is not from the particle to the bottom, but instead it is the distance of the average pore space within the wetland (Kadlec and Wallace, 2009). The average bed porosity of a subsurface flow wetland ranges from 0.30-0.40, making the average pore space distance small compared to the length of the wetland (Kadlec and Wallace, 2009). This settling causes solids to build up on the bottom of the wetland overtime causing hydraulic problems for the wetland. This remains a major maintenance issue because it can cause hydraulic failure and flooding of the wetland.

A few literature sources list the factors that affect solids removal within a wetland setting. These factors are mainly associated with the filtering and interception of particles through the wetland. The factors include:

A) Impaction—solids impact bed particles instead of sweeping past;

B) Diffusional deposition—occurs at both the macro- and micro-scale causing a particle to move to an immersed surface; and

C) Line Interception—particle passes close enough to graze a surface, which alters its path and causes the particle to become retained (Metcalf and Eddy Inc., 1991; Crites and Tchobanoglous, 1998).

These three factors vary in importance depending mainly on the bed material used within the wetland. If the bed material is finer, then A and B will control solids retention, whereas C controls if the bed material is coarser (e.g. gravel) (Kadlec and Wallace, 2009).

Another factor affecting suspended solids retention in a wetland setting is resuspension. When using a subsurface flow wetland, this element (resuspension) is considered negligible because wind and water turbulence are nonexistent. The only source of disturbance may come from burrowing rodents. Another concern for effluent quality is the amount of biofilm that may detach and pass out of the system. A wetland produces mainly biological solids in the form of plant material and biofilm, with chemical precipitation playing a minor role (Kadlec and Wallace, 2009). Biofilm will entrap the solids moving through the system and tend to be most abundant near the entrance of the wetland because that has the highest concentration of organics. Thus the solids leaving a wetland system are usually not the same composition as those entering the system (Kadlec and Wallace, 2009).

Studies have shown that solids removal in constructed wetlands is consistently high and there appears to be no seasonal variability. The seasonal variability is considered to be anywhere from 2-12% of the effluent suspended solids variability (Kadlec and Wallace, 2009). One study with secondary treated wastewater treated by two planted and one unplanted cells reported retentions of 85, 87, and 92%, respectively (Thomas, 1995). Results from later in the study showed that removals increased to between 95-99% showing that mature vegetation with a more complex root system may increase retention efficiency (Thomas, 1995). A system reported by Mæhlum (1995) operated for two years attempting to observe the effects a cold climate would have on a wetland system saw 73% suspended solids retention. This study only operated for two years and treatment was shown to improve with the age of the wetland, so treatment could be expected to improve. Another study used primary effluent and observed 84.3% solids removal with an effluent average of 10.2 mg/L (Vymazal, 2002). An interesting study that used constructed wetlands to treat single family household’s wastewater saw varying results. There were twelve different subsurface flow wetlands that consisted of cattails, polyculture (multiple forms of vegetation), and fescue (a grass) for the vegetated wetlands with unplanted wetlands as controls (Karathanasis *et al.*, 2003). The percent removals for the cattails, polyculture, fescue, and unplanted cells were 90, 90, 88, and 46%, respectively (Karathanasis *et al.*, 2003). It should be noted that the wetlands only met the EPA standard of 30 mg/L once and was attributed to the high influent solids concentrations. The influent concentrations ranged from 418 to 2,102 mg/L, some of the highest currently reported in the literature (Karathanasis *et al.*, 2003). The study concluded that there was a significant difference between the vegetated compared to the unvegetated, and that there was a positive correlation between wetland maturity and TSS retention (Karathanasis *et al.*, 2003).

2.4 Phosphorus Retention

The retention of phosphorus in a constructed wetland system is considered to be limited, but with appropriate design considerations is feasible. Phosphorus is mainly retained within a wetland setting, not removed from the system. The retention of phosphorus is the reason removal is limited. Primary phosphorus retention mechanisms are physical-chemical (precipitation, settling, filtration, and sorption), with biological (plant and bacterial uptake) being minor ones (Kadlec and Wallace, 2009). Orthophosphates are considered the most dominant form within the wetland setting, although there are some polyphosphates and organic phosphate.

Phosphorus is often complexed with organic materials or attached to settled particles, increasing its ability to be filtered or adsorbed. Depending on the nature of the bed materials and characteristics of the influent wastewater, phosphorus can precipitate out by combining with aluminum, iron, calcium, and magnesium, if available. Due to this property of phosphorus (primarily phosphate) the material used for the wetland bed can provide a large reservoir of sorption sites for phosphorus retention. Inconsistent results for phosphorus sorption to specific bed materials make comparisons difficult and there has been poor correlation of results from the lab to the field (Kadlec and Wallace, 2009). High phosphorus retention rates can be observed during the initial stages of operation because sorption sites are not yet filled. Since the number of sorption sites is finite, once capacity is reached the system may no longer retain phosphorus.

Plant uptake can also result in phosphorus retention, although it is not as important as physical processes. Microbes and algae contain an insignificant amount of the total mass (Kadlec and Wallace, 2009). Emergent plants can contain 0.14-0.30% dry weight phosphorus in a natural wetland (Kadlec and Wallace, 2009). Plant uptake of P is variable because of seasonal changes and much of the phosphorus is thought to be returned into the system by the plant detritus. Seventy-five percent of the emerging (above ground) biomass is thought to be lost from the system, but the above ground plant growth has minimal phosphorus content (Tanner *et al*., 1999). Harvesting plants from constructed wetlands would be an ineffective method of phosphorus removal.

A study performed by Tanner *et al.*, 1999, compared phosphorus uptake over a five year period with planted and unplanted constructed wetlands. The total phosphorus removal was higher in the planted wetlands compared to the wetlands with no plants. The planted wetlands showed 1.4-2.0 times greater mean accumulations than the unplanted wetlands (Tanner *et al*., 1999). Plant accumulation only accounted for 9-14% of phosphorus retention during the first two years of operation, but also added phosphorus to the system (Tanner *et al*., 1999). The root zone of the plants provided increased oxygen concentrations and produced plant biomass, which could serve to enhance P sorption. This biomass became organic matter that the phosphorus could attach to and become retained. The higher oxygen concentrations allowed for favorable redox conditions that increased sorption and precipitation (Tanner *et al*., 1999). The phosphorus retention rates after five years showed that no further accumulation was taking place within the bed, but instead the accumulation was closely associated to the plant uptake and organic matter supplied by the plants and influent water (Tanner et al, 1999). Another study showed that as the phosphorus load increased, the retention efficiencies decreased from 71.2% to 31.9% (Lin *et al.*, 2002). This study used a FWS followed by a SSF so removal efficiencies were higher than for a typical SSF wetland. The study period was also only six months so there were a large amount of sorption sites available. The study did show a correlation between phosphorus loading rate and retention of phosphorus. The retention rate increased to a peak as the phosphorus loading increased, but then leveled off. The initial increase of phosphorus retention is caused by the increase in the influent concentration, which increased sorption. Once this sorption was at capacity the retention rate dropped off considerably. The removal rate maximized at 4.1 lb P/ac-d at a loading rate of 8.03 lb P/ac-d (Lin *et al.*, 2002).

2.5 Wetland Hydraulics

Hydraulic modeling of a wetland is crucial to predicting accurate pollutant removal rates. Flow patterns can be established within a wetland causing short-circuiting. Wetland stratification is a recognized issue with horizontal subsurface flow wetlands that can cause various treatment zones throughout a wetland (Kadlec and Wallace, 2009). Vegetative subsurface flow wetlands show preferential flow near the bottom of a wetland if the root zone doesn't extend the full depth. A tracer test can be performed to evaluate the volumetric efficiency of a wetland. Volumetric efficiency is given by:

$$e_v = \frac{\tau}{\tau_n} \qquad \text{(Eq. 2-1)}$$

where τ is the tracer test detention time (days); and τ_n = V/Q = nominal detention time (days).

A tracer test using a pulse input has shown to have exit concentrations that are typically bell-shaped. Studies have shown that wetlands can be represented by neither a plug-flow nor a single completely-mixed reactor (Kadlec and Wallace, 2009). The bell-shaped curve is consistent with consecutive completely mixed tanks. The mass of tracer recovered is represented by the following:

$$M_0 = \int_0^\infty Q_0 C dt = M_i \qquad \text{(Eq. 2-2)}$$

where M_0 and M_i are the initial and final mass (grams); Q_0 is the initial flow rate (m^3/d); t is time (days); and C is the effluent concentration (mg/L) . Tracer detention time is found by the following.

$$\tau = \frac{1}{M_i} \int_0^\infty tQC dt \qquad \text{(Eq. 2-3)}$$

Data collected from a tracer test can then be used to develop pollutant removal rates and one method of doing this is the tanks-in-series (TIS) model. The TIS model uses the parameter N, which represents the effective number of tanks. N is found by the following:

$$\frac{\tau - \tau_{peak}}{\tau} = \frac{1}{N} \qquad \text{(Eq. 2-4)}$$

The number of tanks, N, is then used in the following:

$$\frac{(C - C^*)}{(C_i - C^*)} = (1 + \frac{k\tau}{Nh})^{-N} \qquad \text{(Eq. 2-5)}$$

where k is the effective first order rate coefficient (m/d); h is the free water depth (m); C* is the background concentration (mg/L); C and C_i are the effluent and influent concentrations (mg/L), respectively. This equation can be used to represent the removal of a single compound throughout a wetland.

Modeling parameters that consist of several different compounds such as BOD, TSS, or TN the P-k-C* model is recommended:

$$\frac{(C - C^*)}{(C_i - C^*)} = (1 + \frac{k}{Pq})^{-P} \qquad \text{(Eq. 2-6)}$$

where q is the hydraulic loading rate (m/d); and P is apparent number of TIS. P is the parameter that accounts for different fractions of a mixture degrading at different rates (Kadlec and Wallace, 2009). Studies have shown that P is always less than N because the different rates cause a reduction in the N-value of the wetland.

To find the model coefficients of both the TIS and P-k-C* models, a spreadsheet can be set-up to solve for the parameters. The TIS model can be set-up to have SOLVER evaluate a rate coefficient, k, by reducing the amount of error between all of the data sets. The P-k-C* model has essentially three variables that could be considered unknowns, P, k, and C*. The following rules have been developed when using the model to effectively choose which of the constants to solve for (Kadlec and Wallace, 2009):

1. If $C_i >> C^*$, then it is better to guess a C* and find good estimates of k and P;
2. If $C_i < 3C^*$ it is better to guess P<N and find good estimates of k and C*.

C* represents the background concentration that can result from any of the following:

- Portion of pollutant is resistant to storage or degradation;
- Portion of pollutant is associated with particulates;
- Wetland processes that provide inputs to the system; and
- Seasonality changes that cause surfaces to become dried-out or rewetted which can result in chemical transformations (Kadlec and Wallace, 2009).

The equation can then be set-up to again use SOLVER to determine the best fits for two of the three variables, with the third variable assumed.

CHAPTER 3
THE UNIVERSITY OF IOWA TREATMENT WETLAND RESEARCH FACILITY DESIGN AND CONSTRUCTION

3.1 Introduction

Pilot-scale subsurface flow wetlands were installed at the Iowa City South Wastewater Treatment Plant near Iowa City, Iowa in September 2008 to allow comparison of the effects of aeration and vegetation. The facility consists of eight wetlands that are separated into four different classifications that include variations of aeration/no aeration and vegetation/no vegetation with two replicates for each treatment. The set-up was designed and constructed by Matthew Reusswig to allow demonstration of nitrogen removal in cold weather climates. The wetlands have primarily been monitored for different forms of nitrogen (TN, NH_3, NO_3^-), water temperature and pH. There has been intermittent monitoring of CBOD, COD, phosphorus (PO_4^-), dissolved oxygen (DO) and TSS.

3.2 Treatment Wetland Research Facility (TWRF) Design

3.2.1 Wetland Layout

The wetlands are grouped into four sets of two wetlands each with the sets representing different forms of treatment. Each wetland is eight feet by eight feet and has a depth of two feet. The bottom one foot consists of pea gravel, considered the treatment depth, and the upper foot contains a layer of mulch for insulation. The cells are arranged in the following format:

- 1 & 3 are unplanted and unaerated

- 2 & 4 are unplanted and aerated
- 5 & 7 are planted and unaerated
- 6 & 8 are planted and aerated.

The numbering of the wetlands starts on the left when facing the pumphouse, with the back cells being odd numbers and the front cells being even. The wetlands are lined with an impermeable geomembrane liner made out of an ethylene propylene diene monomer (EPDM) to ensure no wastewater leaks into the surrounding environment. A pump house is situated in the middle of the four sets of wetlands to receive and distribute wastewater. Small sampling ports are set-up in two rows, three deep within each wetland to allow for sampling of both the width and length of the wetland. A viewing port is also located within each wetland to monitor the water height and assure constant hydraulic residence time.

3.2.2 Flow Scheme

Influent wastewater is retrieved via a pump located at the effluent of a primary clarifier. The wastewater is pumped into the pump house where it is distributed to each wetland via a RainBird® EPS-LX programmable solenoid valve control panel (RainBird Corporation, Azusa, CA). The RainBird® is set to dose each wetland for one minute each every six hours throughout the day. Water is pumped into the entrance of the wetland from the top of the treatment depth across the entire width of the wetland. Once the water has flowed through the wetland it is collected at the bottom of the wetland via a perforated pipe across the width of the wetland. The effluent wastewater then travels back to the pump house and exits through height adjustable piping. The height adjustable piping allows for control of the wetland depth. The wastewater is then recycled to the front of the treatment plant to be treated.

Effluent flow was measured by tipping buckets and the influent by the digital flow meter. The tipping buckets were calibrated by recording the number of tips each set-up took per thirty-five liters. The calibration of each bucket was performed twice and the average number of tips was used. It became apparent shortly after installation that the calibration method was off because of the inability to place the buckets level. A field calibration of each bucket was performed by measuring the amount of water it took to cause the buckets to tip. These new calibration numbers were the numbers used to determine the effluent flow.

3.2.3 Aeration System

The aerated wetlands are provided aeration at a rate of approximately 25-30 scfh and provided by tubing running the length of each wetland with a ¾ inch diameter. Aeration is provided at six hour intervals of on and off by a Pondmaster AP-100 air compressor (Danner Mfg., Islandia, NY). One inlet tube runs the width of the wetland with six equally placed perforated tubes stemming out from it run the length of the wetland. Air flow can be adjusted within the pump house via air flow meters.

3.2.4 Vegetation

Planted wetlands are planted with *Scirpus atrovirens* (Dark Green Bulrush). This plant is classified with a moderate reproduction rate, and can reproduce sexually or asexually via seeds and sprigs (i.e. stems) or shoots, respectively (USDA “Plants Database”, 2012). The rooting depth of the dark green bulrush is one foot, which would extend through most of the treatment zone. Bulrush were planted with an initial planting density of approximately one plant per square foot. It was thought that the plant density would increase by an order of magnitude when the wetlands became fully matured. This was observed in the wetland cells that were aerated. A loss of density was observed in the unaerated cells and they had to be replanted during the 2011 Summer to increase the density. It is not known if the loss of density is due to the cells being unaerated or other factors.

3.2.5 Cold Weather Modifications

The wetlands were chosen to be subsurface flow wetlands to allow for an upper layer of mulch for insulation. This insulation is needed to prevent the wetlands from freezing during an Iowa winter where temperatures are frequently below freezing. Water piping provided to the wetlands is kept below ground to prevent freezing. Where the piping appears above ground, it is insulated and wrapped with heat tape.

3.3 TWRF Modifications

There have been numerous modifications to the wetlands since the initial construction. A digital flow meter was added at the inlet piping that can measure total and batch amounts, and instantaneous flow (Great Plains Industries, Inc., Wichita, KS). The digital flow meter appears before the branching of the piping to each wetland so only the flow going to all of the wetlands can be monitored at once. Tipping buckets were designed and added to catch effluent wastewater from the wetlands. Each wetland is equipped with an individual tipping bucket connected to a data logger. Aeration line insulation was needed because where the lines were exposed to the elements during cold weather months they experienced freezing. The aeration lines were wrapped with heat tape and further incased within an insulating cover. Larger sampling ports were added to each wetland that could house a HydroLab (Hach Hydromet, Loveland, CO) to actively collect real-time data and for other sampling purposes. These larger ports were located two feet into the wetlands from the inlet and spaced equally across the width of each wetland.

CHAPTER 4
MATERIALS AND METHODS

4.1 Experimental Set-up

Producing a water balance of the entire system was accomplished via the digital flow meter (Great Plains Industries, Inc., Wichita, KS) coupled with the tipping buckets. Data from the digital flow meter were collected weekly to give a weekly total dosing to all of the wetlands. Flows to individual wetlands were recorded once a week by physically recording the flow meter after each wetland was dosed. These numbers were then compared to the tipping bucket data collected by the data logger every six hours corresponding to the dosing times. Theoretically each six hour period would correspond to the amount of flow caused by the previous dosing. A rain gauge was also installed to factor precipitation into the water balance.

4.2 Sampling Scheme

Sampling occurred on a weekly basis from December 2010 to April 2012. Grab samples were retrieved via the effluent portals located within the pump house. Samples collected from December 2010 until November 17, 2011 were sampled two hours into a six hour aeration period. After November 17, 2011, the sampling time was moved to the end of an aeration period to observe maximum or minimum concentrations. Sampling in all cases did not occur until two minutes and thirty seconds after dosing was finished. This was to ensure the effluent piping had sufficiently been cleared of stale wastewater.

Sampling over an entire aerated and unaerated period (12 hours) was performed to observe variability in concentrations of selected parameters on January 23, 2012. Samples were collected via the two large sampling ports located two feet from the inlet and spaced equally across the width. The ports within the aerated wetlands showed that aeration was provided to different zones of the wetlands, as some ports showed much higher DO concentrations. Samples were only taken from one port within each wetland. Samples from the aerated wetland were taken from the port with the lowest DO concentration. The port to the left of the inlet was arbitrarily chosen in the unaerated wetlands to remain consistent in each.

4.3 Analytical Methods

4.3.1 Ammonia Nitrogen

Ammonia was measured weekly using an EPA equivalent method (Approved General-Purpose Methods, 2012). TNT832 (Hach Company, Loveland, CO) was used along with the standards and blanks. The recommended standard for the procedure was used as well as an internal standard that was created containing ammonia, nitrate, and organic nitrogen. The internal standard consisted of 10 mg NH_3-N /L, 11.3 mg NO_3^- N/L, and 10 mg N/L β-Alanine. The test had a range of 2-47 mg NH_3-N/L and all tests that received a below range concentration were assigned a < 2 mg NH_3-N/L concentration.

4.3.2 Nitrate Nitrogen

Nitrate was measured weekly using a Hach TNTplus kit. TNT835 was used along with standards and blanks (Hach Company, Loveland, CO). The recommended standard for the procedure was used as well as an internal standard. The test had a range of 0.23-13.5 mg NO_3^--N/L and all tests that were below range concentration were assigned a < 0.23 mg NO_3^--N/L concentration.

4.3.3 Total Nitrogen

Total nitrogen was measured weekly using a Hach TNTplus kit. TNT827 or TNT828 (Hach Company, Loveland, CO) was used along with standards and blanks depending upon the expected concentration of the samples. The recommended standard for the procedure was used as well as an internal standard. The high range kit had a range of 20-100 mg N/L and the low range kit had a range of 5-40 mg N/L. Any test that was below range concentration was assigned a < 5 mg N/L concentration.

4.3.4 Total Kjeldahl Nitrogen (TKN)

Total Kjeldahl Nitrogen (TKN) is the sum of organic nitrogen, ammonia, and ammonium. This was calculated by subtracting nitrate-N from TN. Nitrite-N was not tested and was assumed to be zero. This assumption was based on the results from State Hygenics Lab at The University of Iowa that showed a maximum nitrite-N concentration of 0.07 mg NO_2^- -N/L for all of the wetlands

4.3.5 pH

The grab samples were measured for pH using an Orion 915600 probe (Thermo Electron Corporation, Woburn, MA) with an Accumet AB15 pH meter (Thermo Fisher Scientific,Waltham, MA).

4.3.6 Dissolved Oxygen

Dissolved Oxygen was measured from the larger sampling ports periodically. The concentration was measured with a Portable Hach LDO® probe coupled with an HQ20 meter (Hach Company, Loveland, CO).

4.3.7 Phosphorus

Phosphorus was tested bi-weekly starting in the Fall of 2011 using PhosVer® 3 Phosphate Reagent Powder Pillows (Hach Company, Loveland, CO). The method is an EPA accepted method (Approved General-Purpose Methods, 2012).

4.3.8 Chemical Oxygen Demand (COD)

The chemical oxygen demand (COD) of each sample was measured weekly starting in the Fall of 2011 using a TNT822 kit (Hach Company, Loveland, CO). The kit uses an EPA approved method (Approved General-Purpose Methods, 2012).

4.3.9 Carbonaceous Biochemical Oxygen Demand (CBOD)

The CBOD samples were taken every other week or when possible. The samples were tested by the Iowa City South Wastewater Treatment lab staff using the EPA Approved Method 5210B.

4.3.10 Temperature

Temperature was collected using real-time temperature sensors placed into each wetland. These sensors were connected to data loggers powered by solar panels.

4.3.11 Total Suspended Solids (TSS)

Total suspended solids was measured periodically throughout the study. It was measured using EPA Approved Method 160.2 (Approved General-Purpose Methods, 2012).

4.3.12 Hygienics Lab Comparison

Samples were taken to the State Hygienics Lab at The University of Iowa (SHL) to confirm results from our lab. This was done to assure the accuracy of the results because the TN and nitrate nitrogen methods were not EPA approved methods. Composite samples were collected and tested by both the SHL's lab and our lab.

4.4 Tracer Study

4.4.1 Materials

Potassium Bromide was used to perform a tracer test on each of the wetland cells. Effluent bromide concentration was measured using a Thermo Scientific Orion bromide electrode ionplus® Sure-Flow® (Thermo Fisher Scientific, Waltham, MA) with an Accumet Excel XL25 pH/mV/Temperature/ISE Meter (Thermo Fisher Scientific, Waltham, MA).

4.4.2 Methods

Potassium Bromide was placed into the holding tank within the pump house. The holding tank collects the primary effluent wastewater to be distributed to the wetlands. A known amount of potassium bromide was placed into the empty tank and the tank was then filled with a known amount of wastewater. The wetlands were then dosed and the amount of each dose was recorded to accurately measure the mass to each wetland. This was done three times because the volume of the holding tank could only hold enough water for three dosing cycles at a time. Effluent samples were then collected and tested for bromide concentration. These tests were performed until the concentration was equal to that of the background concentration.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Wastewater Influent and Effluent General Characteristics

The effluent results (Table 3) closely match that of comparable treatment wetlands with comparable influents from literature. Meeting effluent requirements for discharge of wastewater requires the monitoring of multiple contaminants with maximum discharge limits. The major focus of this study was on nitrogen removal, with periodic measurements of phosphorus, COD, TSS, and CBOD.

The results for the duplicate wetland cells are combined into one data set with the exception of the results from the two planted and aerated cells. All the duplicate cell results were tested for significance ($p < 0.05$) and only the two planted and aerated cells were determined to be significantly different from each other (Mendenhal and Sincich, 2007). The results from these two cells will be compared separately throughout the thesis.

The effluent concentrations for TSS and CBOD (Table 3) show that all wetland cells effectively remove these pollutants to levels less than the 25 mg/L discharge limit. The aerated wetland cells show phosphorus retentions from 53.2 to 73.5%, while the unaerated wetland cells have retentions ranging from 12.7 (unplanted) to 22.7% (planted). These results are comparable to the results reported by *Tanner et al.* (1999) who found that planted wetlands retained phosphorus 1.4-2.0 times better than non-planted wetlands. The same study showed that higher oxygen concentrations within planted cells impacted redox conditions to favor increased sorption and precipitation (Tanner *et al*., 1999). The higher oxygen concentrations and resultant redox conditions are likely the explanation for the higher performance of the aerated versus unaerated wetland cells. Ammonia removals for aerated wetland cells ranged from 82.2 to 95.3%, while for the unaerated wetland cells ranged from 39.0 to 44.6%. This difference is a direct result of aeration allowing nitrification to occur.

Table 3. Influent and Effluent Wastewater Characteristics over the entire study period.

Waste Source	Pollutant	Average Concentration ± Std. Dev.	Removal/Retention Percentage ± Std. Dev.
Influent	Total Nitrogen (mg N/L)	45.9 ± 10.1	--
	Ammonia Nitrogen (mg N/L)	34.3 ± 8.3	--
	Phosphorus (mg PO4-/L)	7.0 ± 1.5	--
	TSS (mg/L)	109 ± 40.3	--
	COD (mg/L)	638 ± 212	--
	CBOD (mg/L)	181 ± 47.8	--
Unplanted/ Unaerated	Total Nitrogen (mg N/L)	23.1 ± 4.7	51.4 ± 11.9
	Ammonia Nitrogen (mg N/L)	22.8 ± 4.8	44.6 ± 14.0
	Phosphorus (mg PO4-/L)	6.18 ± 0.81	12.7 ± 18.1
	TSS (mg/L)	8.18 ± 5.29	94.2 ± 3.4
	COD (mg/L)	122 ± 38.4	80.4 ± 8.0
	CBOD (mg/L)	19.7 ± 8.61	88.8 ± 4.9
Unplanted/ Aerated	Total Nitrogen (mg N/L)	9.5 ± 4.6	80.2 ± 10.9
	Ammonia Nitrogen (mg N/L)	5.7 ± 3.9	82.2 ± 12.5
	Phosphorus (mg PO4-/L)	4.2 ± 1.6	53.2 ± 20.7
	TSS (mg/L)	5.0 ± 5.6	96.4 ± 2.3
	COD (mg/L)	84.1 ± 27.5	89.3 ± 3.2
	CBOD (mg/L)	7.0 ± 4.8	96.8 ± 1.6
Planted/Unaerated	Total Nitrogen (mg N/L)	23.8 ± 4.6	49.8 ± 10.5
	Ammonia Nitrogen (mg N/L)	21.9 ± 3.8	39.0 ± 13.7
	Phosphorus (mg PO4-/L)	5.8 ± 0.8	22.7 ± 17.3
	TSS (mg/L)	5.1 ± 4.1	96.9 ± 1.5
	COD (mg/L)	112 ± 42.6	83.7 ± 6.9
	CBOD (mg/L)	15.9 ± 8.2	90.1 ± 4.2
Planted/Aerated (6)	Total Nitrogen (mg N/L)	8.7 ± 2.7	88.0 ± 5.6
	Ammonia Nitrogen (mg N/L)	2.7 ± 1.3	95.3 ± 1.3
	Phosphorus (mg PO4-/L)	2.9 ± 1.2	73.5 ± 16.1
	TSS (mg/L)	2.3 ± 1.4	98.8 ± 0.7
	COD (mg/L)	52.2 ± 16.4	93.3 ± 3.5
	CBOD (mg/L)	2.6 ± 1.1	98.7 ± 0.6
Planted/Aerated (8)	Total Nitrogen (mg N/L)	12.2 ± 4.8	81.4 ± 10.7
	Ammonia Nitrogen (mg N/L)	6.4 ± 2.7	84.3 ± 9.4
	Phosphorus (mg PO4-/L)	3.54 ± 1.81	56.7 ± 33.6
	TSS (mg/L)	3.9 ± 3.7	98.0 ± 1.1
	COD (mg/L)	66.0 ± 31.2	91.1 ± 4.4
	CBOD (mg/L)	3.2 ± 1.4	98.3 ± 0.6

5.2 COD/CBOD Results

The influent wastewater organic carbon is a concern when evaluating the effectiveness of the nitrification/denitrification process. For every gram of nitrate that is reduced 3.02 grams of organic matter are required (Tchobanoglous *et al.*, 2004). COD and CBOD concentrations were measured periodically throughout the study to assess whether the denitrification process was ever carbon limited and to monitor organic removal. The average influent CBOD concentration (Table 3), 181 mg/L, appears to be adequate carbon for denitrification. Using 3.02 g BOD/g nitrate and the average influent ammonia concentrations of 34.3 mg N/L, there needs to be 104 mg/L BOD available. When examining the influent data over the course of the study there was never a measured concentration below 110 mg/L so it could be assumed that, in general, the system is not carbon limited and denitrification could theoretically continue to completion. However, much of the carbon could be consumed by heterotrophs before denitrification takes place causing the system to be possibly become carbon limited.

Figure 2 shows a box-and-whiskers plot of influent and effluent COD concentrations. Figure 3 shows the various removals of each type of treatment using box-and-whisker plots also. Results from the two planted and aerated cells were combined when considering COD effluent concentrations and removals because they were not determined to be significantly different ($p<0.05$) (Mendenhal and Sincich, 2007).

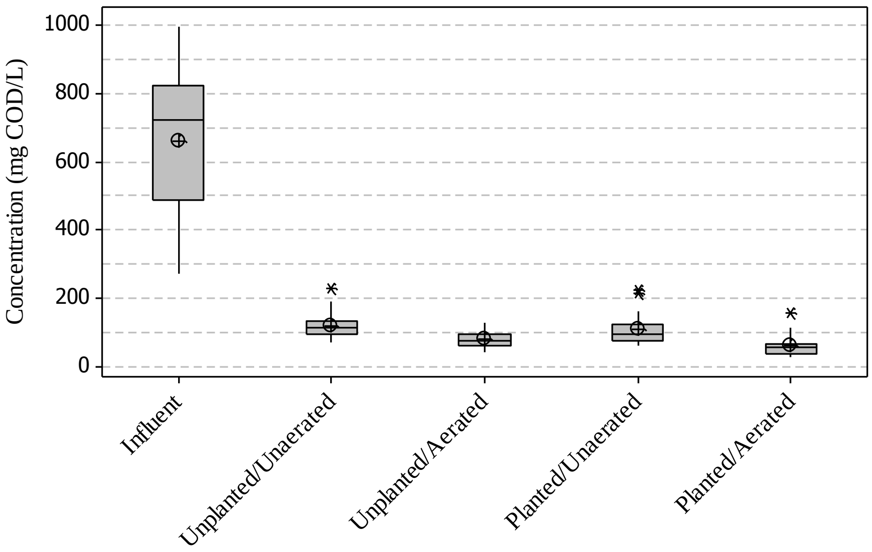


Figure 2. Box-and-whiskers plot showing the upper and lower quartiles for influent and effluent COD concentrations. The asterisks denote an outlier and the circle with crosshairs denotes the mean concentration.

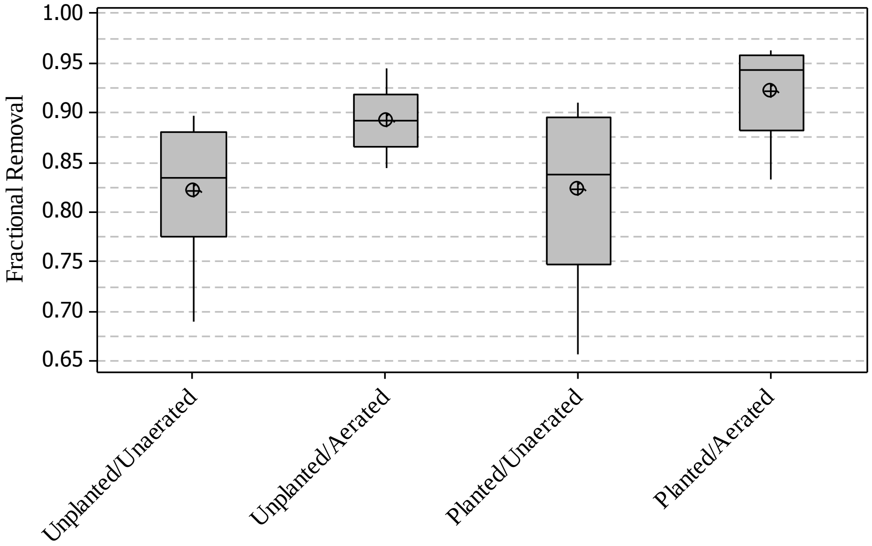


Figure 3. Box-and-whiskers plot showing the upper and lower quartiles for COD removal fractions. The circle with crosshairs denotes the mean removal fraction.

From Figure 2 the COD concentrations for the aerated wetland cells appear to show slightly lower and tighter quartiles suggesting that aeration may provide more consistent overall treatment. It is clearer when comparing the removal fractions that the aerated cells perform consistently better and have more consistent removal percentages shown by the smaller quartile ranges. Effluent concentrations and removal percentages show that there is a significant difference ($p<0.05$) between the aerated and unaerated cells (Mendenhal and Sincich, 2007). There is not a significant difference ($p<0.05$) when when comparing the unplanted cells to the planted cells for both the unaerated and aerated systems.

5.3 Nitrogen Transformations and Removals

Effluent nitrogen concentrations for wastewater discharge are important not only because of regulations, but these are the values that are deemed to be detrimental to receiving waters. The unique set-up at the test facility using side-by-side wetland cells for comparison allows for more comprehensive data sets. To evaluate these data sets sampling was done over a ten day period to determine variability within each wetland as well as between the duplicate wetland cells. The averages and standard deviations of this period are in Table 4.

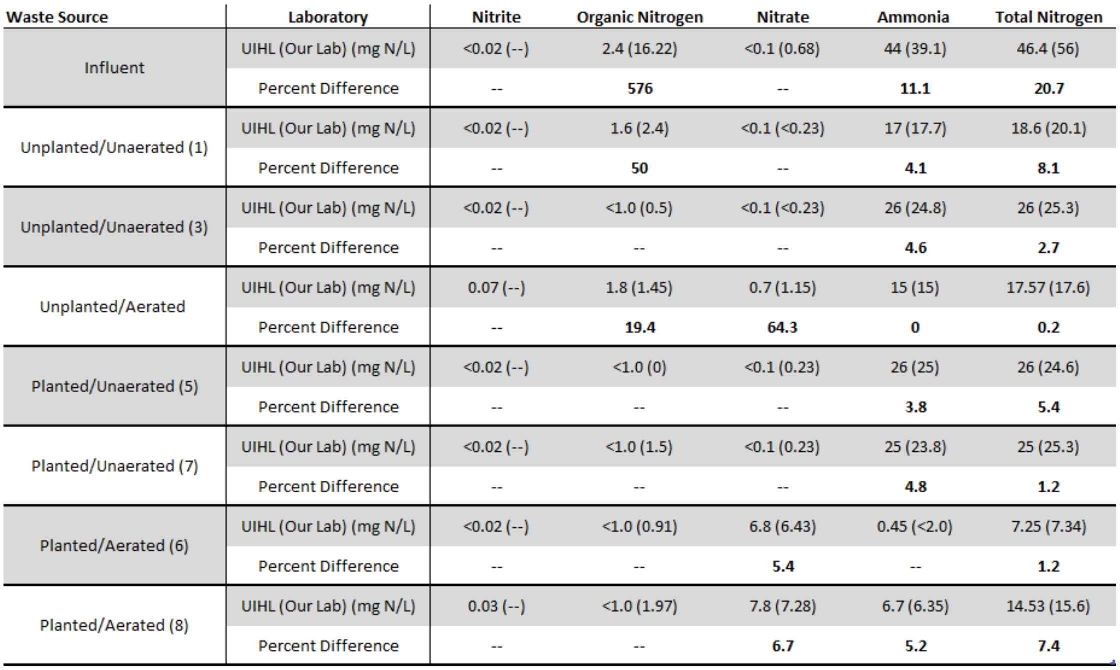
Table 4. Total nitrogen averages and standard deviations over 10 day sampling period.

		Unplanted/Unaerated		Unplanted/Aerated	Planted/Unaerated		Planted/Aerated	
--	**Influent**	**1**	**3**	**2**	**5**	**7**	**6**	**8**
Average (mg N/L)	49.60	20.30	20.6	12.3	22.2	20.4	10.8	17.0
Standard Deviation (mg N/L)	5.30	1.3	1.9	1.1	2.2	1.8	0.7	1.4

Every duplicate cell with the exception of the two planted and aerated cells have standard deviations that overlap and are not significantly different ($p<0.05$) showing that the data is consistent in both duplicates. When comparing the data throughout the study all duplicate cells will be combined and the two planted and aerated cells will be evaluated separately.

The lab testing performed during the study used Hach kits, as stated in Chapter 4, and to test the accuracy, composite samples were sent to the SHL for comparison. Table 5 shows SHL's results compared to the results obtained in our lab.

Table 5. Comparison of lab testing and SHL's results.



Waste Source	Laboratory	Nitrite	Organic Nitrogen	Nitrate	Ammonia	Total Nitrogen
Influent	UIHL (Our Lab) (mg N/L)	<0.02 (--)	2.4 (16.22)	<0.1 (0.68)	44 (39.1)	46.4 (56)
	Percent Difference	--	**576**	--	**11.1**	**20.7**
Unplanted/Unaerated (1)	UIHL (Our Lab) (mg N/L)	<0.02 (--)	1.6 (2.4)	<0.1 (<0.23)	17 (17.7)	18.6 (20.1)
	Percent Difference	--	**50**	--	**4.1**	**8.1**
Unplanted/Unaerated (3)	UIHL (Our Lab) (mg N/L)	<0.02 (--)	<1.0 (0.5)	<0.1 (<0.23)	26 (24.8)	26 (25.3)
	Percent Difference	--	--	--	**4.6**	**2.7**
Unplanted/Aerated	UIHL (Our Lab) (mg N/L)	0.07 (--)	1.8 (1.45)	0.7 (1.15)	15 (15)	17.57 (17.6)
	Percent Difference	--	**19.4**	**64.3**	**0**	**0.2**
Planted/Unaerated (5)	UIHL (Our Lab) (mg N/L)	<0.02 (--)	<1.0 (0)	<0.1 (0.23)	26 (25)	26 (24.6)
	Percent Difference	--	--	--	**3.8**	**5.4**
Planted/Unaerated (7)	UIHL (Our Lab) (mg N/L)	<0.02 (--)	<1.0 (1.5)	<0.1 (0.23)	25 (23.8)	25 (25.3)
	Percent Difference	--	--	--	**4.8**	**1.2**
Planted/Aerated (6)	UIHL (Our Lab) (mg N/L)	<0.02 (--)	<1.0 (0.91)	6.8 (6.43)	0.45 (<2.0)	7.25 (7.34)
	Percent Difference	--	--	**5.4**	--	**1.2**
Planted/Aerated (8)	UIHL (Our Lab) (mg N/L)	0.03 (--)	<1.0 (1.97)	7.8 (7.28)	6.7 (6.35)	14.53 (15.6)
	Percent Difference	--	--	**6.7**	**5.2**	**7.4**

The results confirmed that the Hach kits are fairly accurate, with the exception of the influent comparisons. The influent data shows differences of 576, 11.1, and 20.7%

for organic nitrogen, ammonia, and TN, respectively. Other large differences occurred when measuring near the detection limit which could be responsible for the differences. The results also confirmed our assumption that the wastewater would contain minimal amounts of nitrite (concentrations below 0.02 mg N/L). The high disparities comparing the results obtained from the influent data warranted further investigation. On two separate occasions composite influent samples were collected. Three samples were sent to SHL and three samples were tested by our lab to determine the variability in the influent. The results are shown in Table 6.

Table 6. Influent comparison of lab testing and SHL on two occasions.

		Ammonia	Nitrate	TKN	Organic Nitrogen	Total Nitrogen
Average (Std. Dev.)	UIHL	36.7 (1.15)	0.2 (0.14)	49 (1)	12 (2)	49.1 (0.9)
mg N/L	Lab	34 (0.56)	0.88 (0.02)	--	12.9 (2.2)	47.8 (1.6)
Percent Difference		**7.3**	**338**	--	**7.7**	**2.7**
Average (Std. Dev.)	UIHL	37.7 (2.1)	--	45.3 (5.5)	7.2 (4.7)	45.3 (5.5)
mg N/L	Lab	34.2 (1.2)	0.56 (0.03)	--	8.8 (0.5)	43.6 (1.7)
Percent Difference		**9.3**	--	--	**22.2**	**3.9**

The averages show that the two labs compare well with the exception of nitrate and organic-N. The nitrate differences could again be because the concentrations are near the detection limit. The organic-N difference could be cause by how organic-N is determined in our lab (not measured). Otherwise the percent differences are below 10% and the accuracy of the Hach test is within acceptable range.

5.3.1 Ammonia

Ammonia nitrogen exerts an oxygen demand on receiving waters and will also indicate the efficiency of the nitrification cycle. Table 7 shows the average ammonia nitrogen concentrations as well as the average percent removal achieved.

Table 7. Average ammonia concentrations and percent removals with standard deviations (from 12/23/2010-3/1/2012).

Waste Source	Average Concentration ± Std. Dev. (mg N/L)	Percent Removal
Influent	34.3 ± 8.3	--
Unplanted/ Unaerated	22.8 ± 4.8	44.6 ± 14.0
Unplanted/ Aerated	5.7 ± 3.9	82.2 ± 12.5
Planted/Unaerated	21.9 ± 3.8	39.0 ± 13.7
Planted/Aerated (6)	2.7 ± 1.3	95.3 ± 1.3
Planted/Aerated (8)	6.4 ± 2.7	84.3 ± 9.4

The removal percentages show that the aerated wetland cells are removing, on average, greater than 80%, with the most efficient, planted and aerated wetland cell 6, removing an average of 95%. The unaerated wetland cells on average remove from 39 to 45% of the influent ammonia. Figure 4 andFigure 5 show box-and-whiskers plots of the concentrations and removal fractions, respectively.

From Figure 4 it is apparent that the aerated wetland cells have consistently lower effluent concentrations, shown by the tighter quartile range. The two aerated and planted wetland cells appear to have the most consistent effluent concentrations; however, when the fractional removals are compared, planted and aerated cell 8 appears to have less consistency. This lack of consistency is likely the cause of the two wetland cells being significantly different ($p<0.05$) even though they were designed to be the same. There was a significant difference ($p<0.05$) found between aerated and unaerated wetland cells. Planted wetland cells showed significant difference ($p<0.05$) when comparing the unplanted/aerated wetland cells to the planted/aerated wetland cell 6, but the planted/aerated wetland cell 8 showed no significant difference. These data demonstrate the variability in field-scale wetland cells.

In an attempt to assess the effect of temperature (seasonal), data were separated into ambient air temperature ranges. The ambient air temperature ranges were less than 2°C, 2-20°C, and greater than 20°C because there appears to be no corresponding change in k-values for TKN removal from 2-20°C (Kadlec and Wallace, 2009). The temperature data were taken as a three day average ending on the sample collection date. The temperature ranges and effluent concentrations for the respective wetland cells are in Table 8.

Data in Table 8 show that there is little if any effect of temperature. This could be due to the relatively mild winter Iowa experienced in 2011-2012. The temperature range of less than 2°C has the fewest data points, with a low ambient air temperature of nearly -6°C. The warmest temperature recorded was nearly 33°C, but temperatures greater than 20°C appear to have little to no effect on treatment efficiency. It would be expected for the effluent concentrations to increase as temperature decreases; however, the reverse was observed for some of the wetland cells. The data suggest that lower ambient air temperatures would need to be experienced to significantly affect treatment performance. More data points at the low end of the temperature regime need to be gathered before testing reliably for significant differences between temperature ranges.

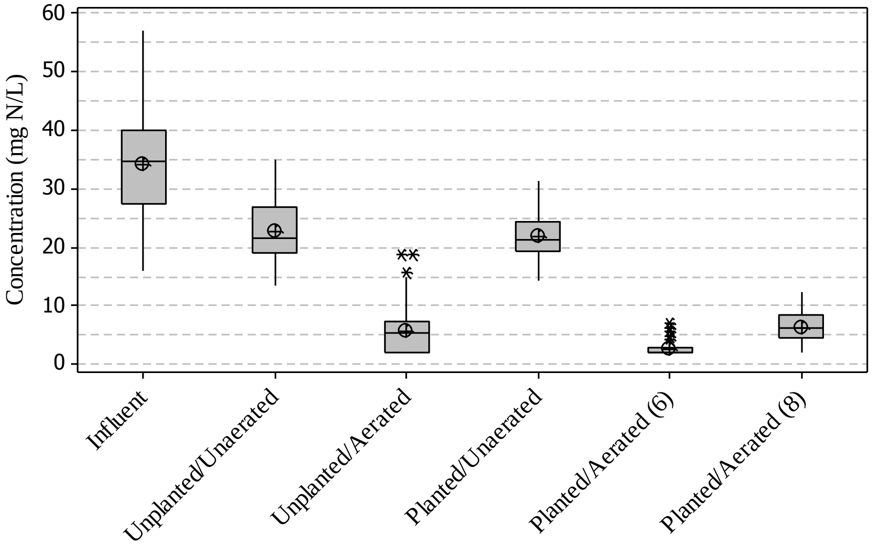


Figure 4. Box-and-whiskers plot showing the upper and lower quartiles for influent and effluent ammonia concentrations. The asterisks denote outliers and the circle with crosshairs denotes the mean concentration.

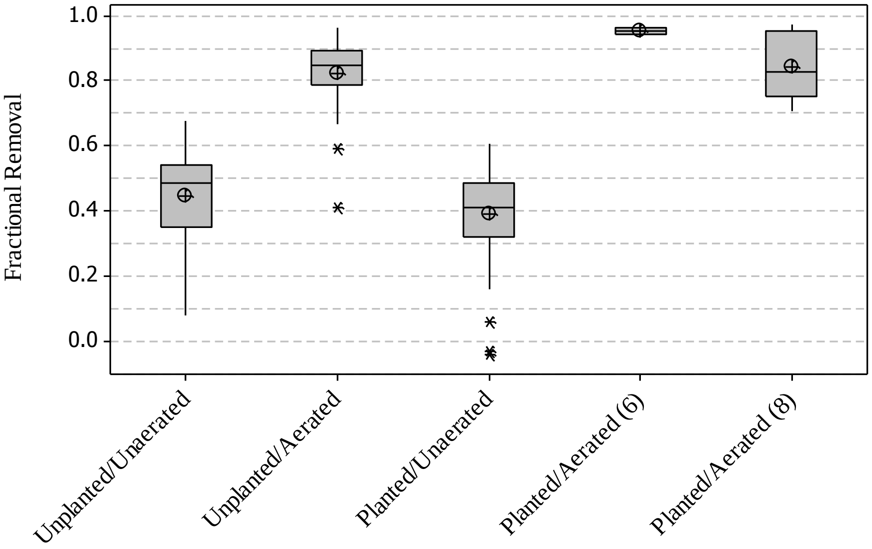


Figure 5. Box-and-whiskers plot showing the upper and lower quartiles for ammonia removal fractions. The asterisks denote outliers and the circle with crosshairs denotes the mean removal fraction.

Table 8. Effluent average ammonia concentrations and standard deviations of three temperature ranges.

	Unplanted/Unaerated			Unplanted/Aerated			Planted/Unaerated			Planted/Aerated (6)			Planted/Unaerated (8)		
	<2°C	2-20°C	>20°C	<2°C	2-20°C	>20°C	<2°C	2-20°C	>20°C	<2°C	2-20°C	>20°C	<2°C	2-20°C	>20°C
n	22	54	34	11	27	23	22	54	34	11	27	17	11	27	17
Average (mg N/L)	23.32	22.46	23.37	4.00	7.65	4.04	21.26	21.86	22.49	2.11	2.90	2.88	7.25	7.40	4.14
Std. Dev. (mg N/L)	5.73	4.16	2.37	2.34	4.53	2.64	3.30	3.18	4.98	0.27	1.42	1.46	2.63	2.35	1.97

The lack of any temperature effect from the three different ambient air temperature ranges is further supported by data in Figure 6 through Figure 10. These figures present the ammonia mass removal rate versus mass loading rate. The high linear relationship for the wetland cells further supports the conclusion that water temperature does not play a role in ammonia removal in aerated, subsurface flow wetlands, at least under the condition studied here.

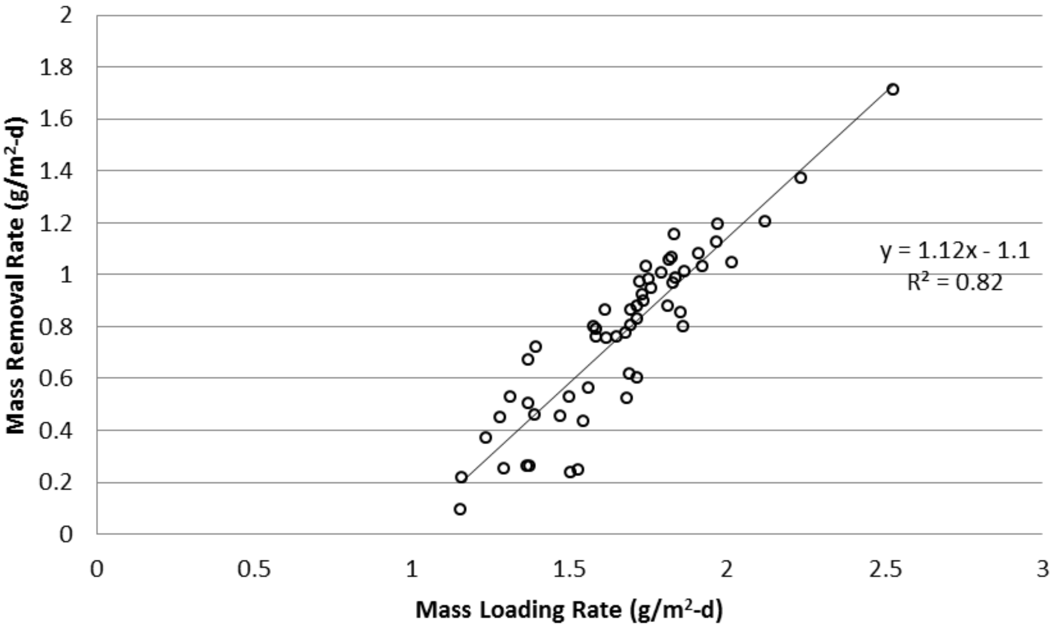


Figure 6. Ammonia mass removal rate vs. mass loading rate for unplanted/unaerated wetland cells (1 & 3).

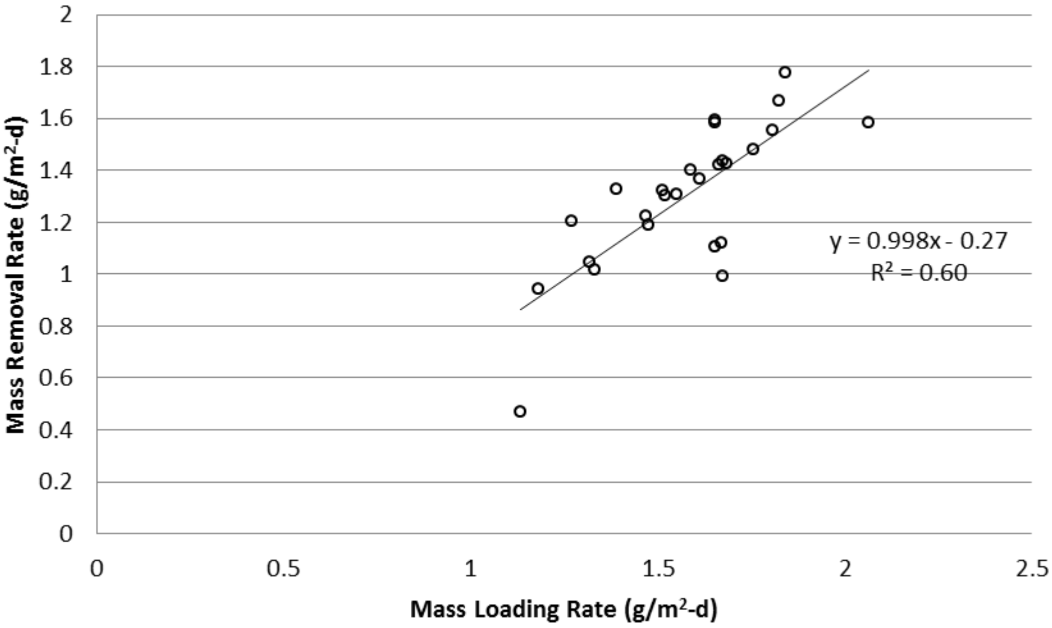


Figure 7. Ammonia mass removal rate vs. mass loading rate for unplanted/aerated wetland cells (2 & 4).

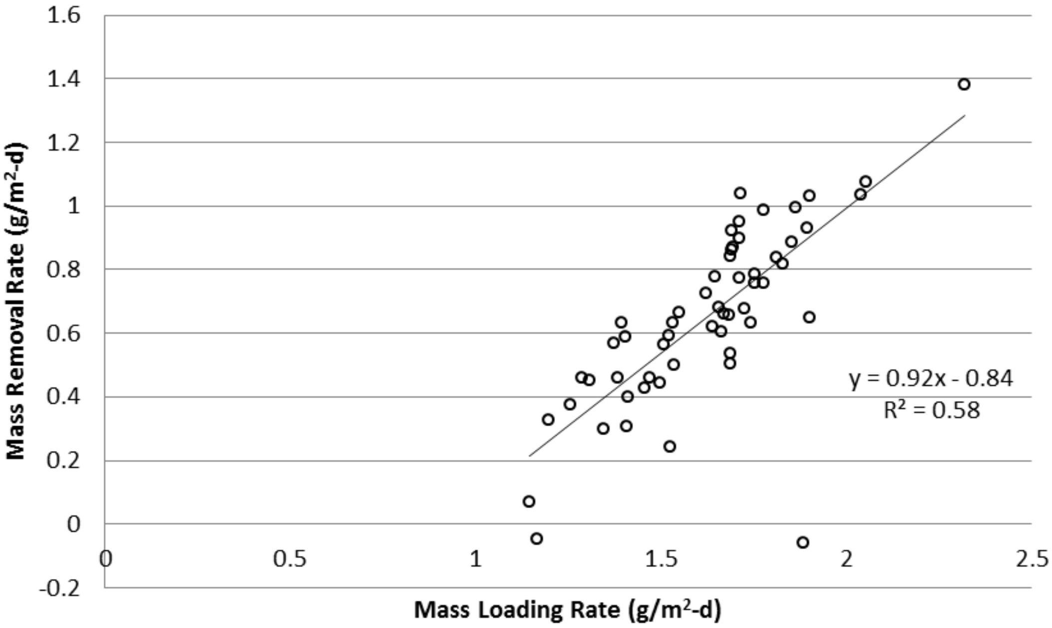


Figure 8. Ammonia mass removal rate vs. mass loading rate for planted/unaerated wetland cells (5 & 7).

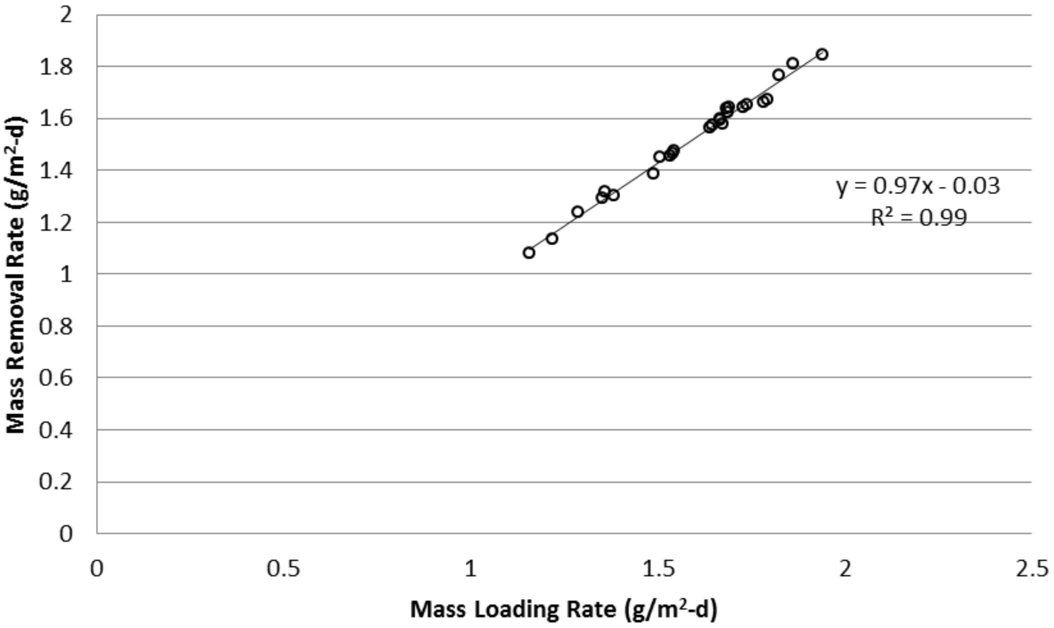


Figure 9. Ammonia mass removal rate vs. mass loading rate for planted/aerated wetland cell 6.

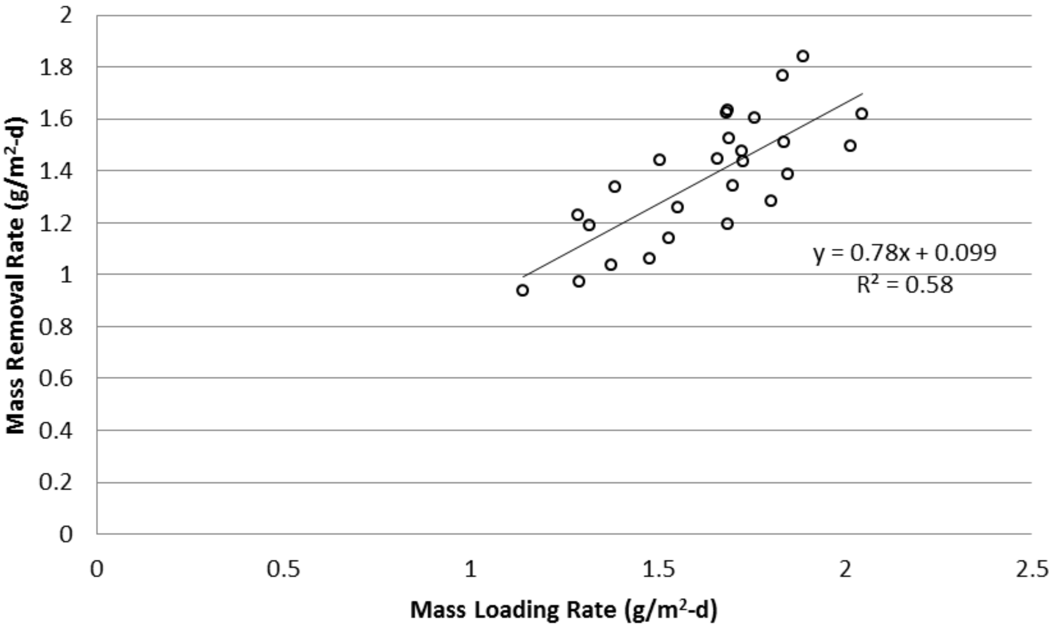
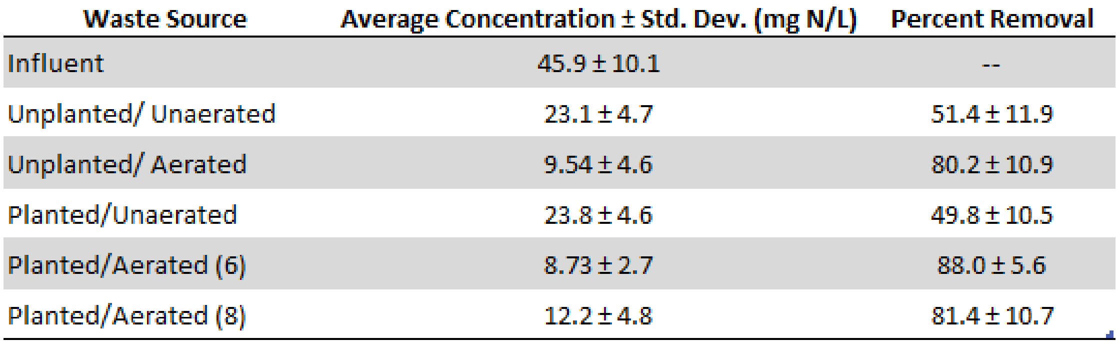


Figure 10. Ammonia mass removal rate vs. mass loading rate for planted/aerated wetland cell 8.

5.3.2 Total Nitrogen

Total nitrogen (TN) is of a concern because it is a measure of all forms of nitrogen. The nitrogen composition in the influent consisted of mainly ammonia and organic nitrogen, which are both considered to exert extra oxygen demand on receiving waters. The average concentrations and percent removals with standard deviations are in Table 9 for TN. There are fewer data for TN than ammonia because of TN testing complications.

Table 9. Average total nitrogen concentrations and percent removals with standard deviations.



Waste Source	Average Concentration ± Std. Dev. (mg N/L)	Percent Removal
Influent	45.9 ± 10.1	--
Unplanted/ Unaerated	23.1 ± 4.7	51.4 ± 11.9
Unplanted/ Aerated	9.54 ± 4.6	80.2 ± 10.9
Planted/Unaerated	23.8 ± 4.6	49.8 ± 10.5
Planted/Aerated (6)	8.73 ± 2.7	88.0 ± 5.6
Planted/Aerated (8)	12.2 ± 4.8	81.4 ± 10.7

Conclusions to be drawn from these data are the same as for ammonia because such a large portion, 75%, of the influent TN is ammonia. The aerated wetland cells show average removals of 80% and higher, while the unaerated wetland cells show removals around 50%. The average TN concentration for the aerated wetlands hovers around 10 mg N/L, which consists of a varying mixture of ammonia and nitrate with very little organic nitrogen present. Figure 11 and Figure 12 show the box-and-whisker plots of the TN concentrations and removal fractions, respectively.

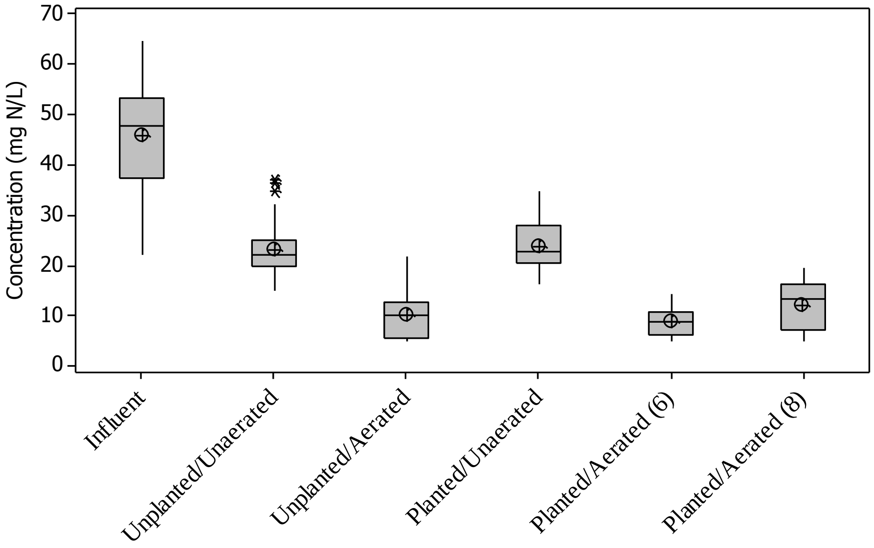


Figure 11. Box-and-whiskers plot showing the upper and lower quartiles for influent and effluent TN concentrations. The asterisks denote outliers and the circle with crosshairs denotes the mean concentration.

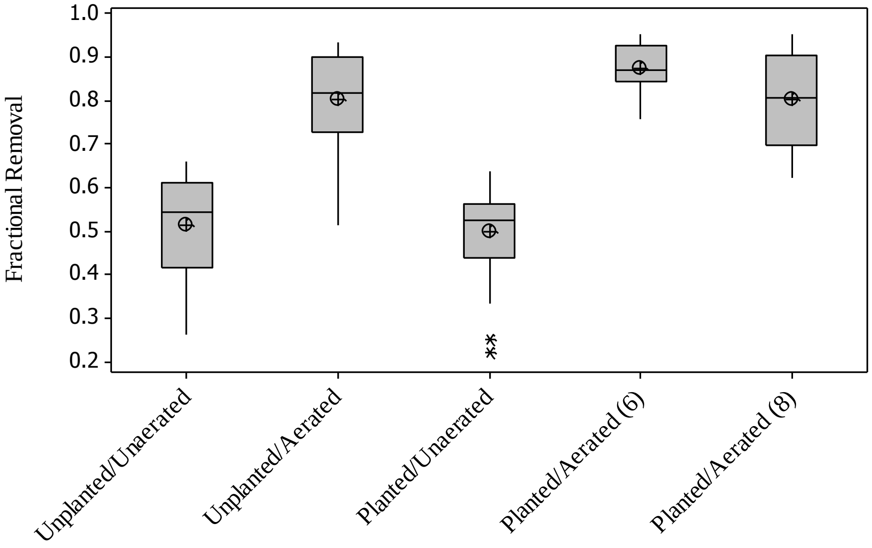
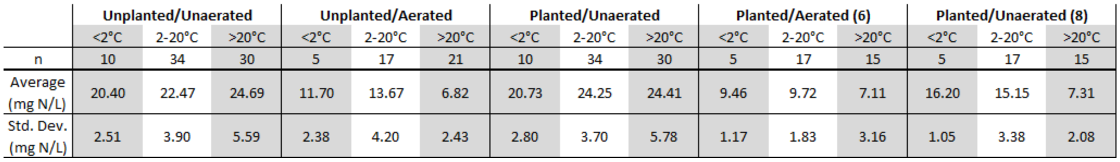


Figure 12. Box-and-whiskers plot showing the upper and lower quartiles for TN removal fractions. The circle with crosshairs denotes the mean removal fraction.

From these data it is apparent that planted and aerated wetland cell 6 has consistent effluent concentrations as well as removal fractions. The unplanted/aerated and planted/aerated 8 wetland cells show wide variations that could be due to numerous causes including: short circuiting, volumetric efficiency (possibly an indicator of short circuiting), and inefficient aeration. The aeration is applied to all aerated wetland cells at approximately the same rate, but anaerobic/anoxic zones have been observed in various locations. The TN data again show that there is a significant difference ($p<0.05$) between the aerated and unaerated wetland cells. There is no significant difference ($p<0.05$) between the planted and unplanted cells.

Data were again separated into ambient air temperature ranges to identify differences in treatment efficiency. The ambient air temperature ranges were again less than 2°C, 2-20°C, and greater than 20°C. The temperature ranges and effluent concentrations for the respective wetland cells are in Table 10.

Table 10. Effluent average total nitrogen concentrations and standard deviations of three temperature ranges.



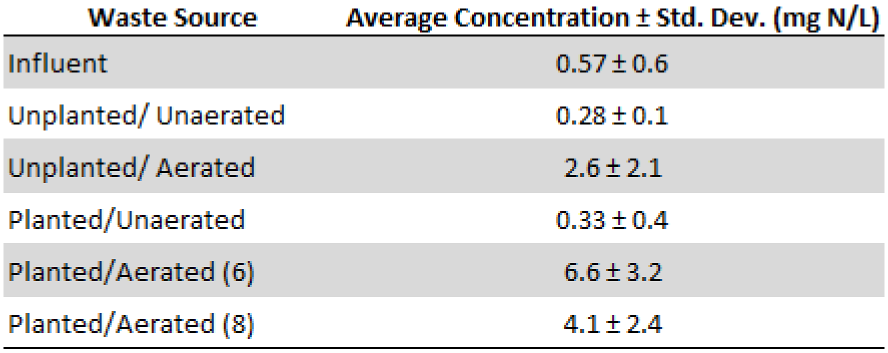
	Unplanted/Unaerated			Unplanted/Aerated			Planted/Unaerated			Planted/Aerated (6)			Planted/Unaerated (8)		
	<2°C	2-20°C	>20°C	<2°C	2-20°C	>20°C	<2°C	2-20°C	>20°C	<2°C	2-20°C	>20°C	<2°C	2-20°C	>20°C
n	10	34	30	5	17	21	10	34	30	5	17	15	5	17	15
Average (mg N/L)	20.40	22.47	24.69	11.70	13.67	6.82	20.73	24.25	24.41	9.46	9.72	7.11	16.20	15.15	7.31
Std. Dev. (mg N/L)	2.51	3.90	5.59	2.38	4.20	2.43	2.80	3.70	5.78	1.17	1.83	3.16	1.05	3.38	2.08

Data in Table 10 again show that there is little if any temperature effect, perhaps due to the relatively mild winter Iowa experienced in 2011-2012. The data again suggest that lower ambient air temperatures would need to be experienced to significantly affect treatment performance. More data points at the low end of the temperature regime need to be gathered before testing reliably for significant differences between temperature ranges.

5.3.3 Nitrate

Nitrate is the result of the nitrification process and can cause several water quality problems. The nitrate entering the wetland system is essentially nil and therefore any nitrate present within the system is the result of nitrification. The influent and effluent nitrate concentrations with standard deviations are presented in Table 11.

Table 11. Average nitrate concentrations with standard deviations.



Waste Source	Average Concentration ± Std. Dev. (mg N/L)
Influent	0.57 ± 0.6
Unplanted/ Unaerated	0.28 ± 0.1
Unplanted/ Aerated	2.6 ± 2.1
Planted/Unaerated	0.33 ± 0.4
Planted/Aerated (6)	6.6 ± 3.2
Planted/Aerated (8)	4.1 ± 2.4

The average nitrate concentrations for the unaerated wetland cells and the influent are near the detection limit of 0.23 mg N/L. The nitrate concentrations for the aerated wetlands correspond well with the removals reported earlier for ammonia nitrogen. Planted/aerated wetland cell 6 had the highest removals of ammonia and also has the highest nitrate concentrations. The same is true for planted/aerated 8 and unplanted/aerated wetland cells with the higher ammonia removal corresponding to a higher nitrate concentration. This could indicate that a considerable portion of nitrification is occurring near the end of the wetland cells or the system could be carbon limited, both of which could limit denitrification.

5.3.4 Organic Nitrogen

Organic nitrogen is combined with the ammonia to make up total Kjeldhal nitrogen (TKN). This measurement is important because of the potential for organic nitrogen to be converted into ammonia and exert an oxygen demand. Organic nitrogen concentrations were obtained by using the difference between TN concentrations and the sum of nitrate and ammonia concentrations; nitrite concentrations were assumed to be zero. Table 12 shows the average concentrations and standard deviations of the organic nitrogen concentrations.

Table 12. Average organic nitrogen concentrations with standard deviations.

Waste Source	**Average Concentration ± Std. Dev. (mg N/L)**
Influent	10.8 ± 4.3
Unplanted/ Unaerated	1.6 ± 1.3
Unplanted/ Aerated	1.9 ± 1.0
Planted/Unaerated	1.4 ± 1.4
Planted/Aerated (6)	1.2 ± 1.8
Planted/Aerated (8)	1.7 ± 1.4

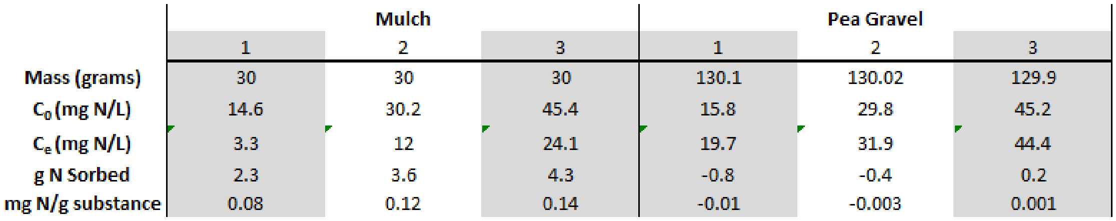
The data show that obtaining organic nitrogen by finding the differences of other measured concentrations results in highly consistent data. The standard deviations that are larger than the average concentrations show that the sum of ammonia and nitrate nitrogen was sometimes more than the measured TN concentration. To gain a more effective representation of the treatment efficiency for organic nitrogen testing that specifically measures organic nitrogen is recommended. The data do show that all of the wetland cells, regardless of plants or aeration, remove organic nitrogen down to approximately 1.5 mg N/L. The treatment efficiency is approximately 85%, determined using average concentrations.

5.4 Adsorption and Desorption Analysis

Ammonia removals have shown to be considerably less than 50% because of the anaerobic nature of unaerated, subsurface flow wetlands. Studies have shown removals ranging from 14-40%; removals of our wetland cells were from 39 to 45% (Nivala *et al.*, 2007; Thomas, 1995). To explain this removal, sorption and desorption tests were performed in the lab.

A sorption test was performed using mulch and pea gravel from the wetland cells. Three sets of each material were used along with three initial ammonia concentrations (15, 30, and 45 mg N/L). These samples were allowed to sit for 24 hours with no atmospheric interchange. The results from the test are in Table 13 and a Fruendlich isotherm was developed in Figure 13.

Table 13. Adsorption test initial and final conditions using ammonia nitrogen adsorbing to mulch and pea gravel.



	Mulch			Pea Gravel		
	1	2	3	1	2	3
Mass (grams)	30	30	30	130.1	130.02	129.9
C_0 (mg N/L)	14.6	30.2	45.4	15.8	29.8	45.2
C_e (mg N/L)	3.3	12	24.1	19.7	31.9	44.4
g N Sorbed	2.3	3.6	4.3	-0.8	-0.4	0.2
mg N/g substance	0.08	0.12	0.14	-0.01	-0.003	0.001

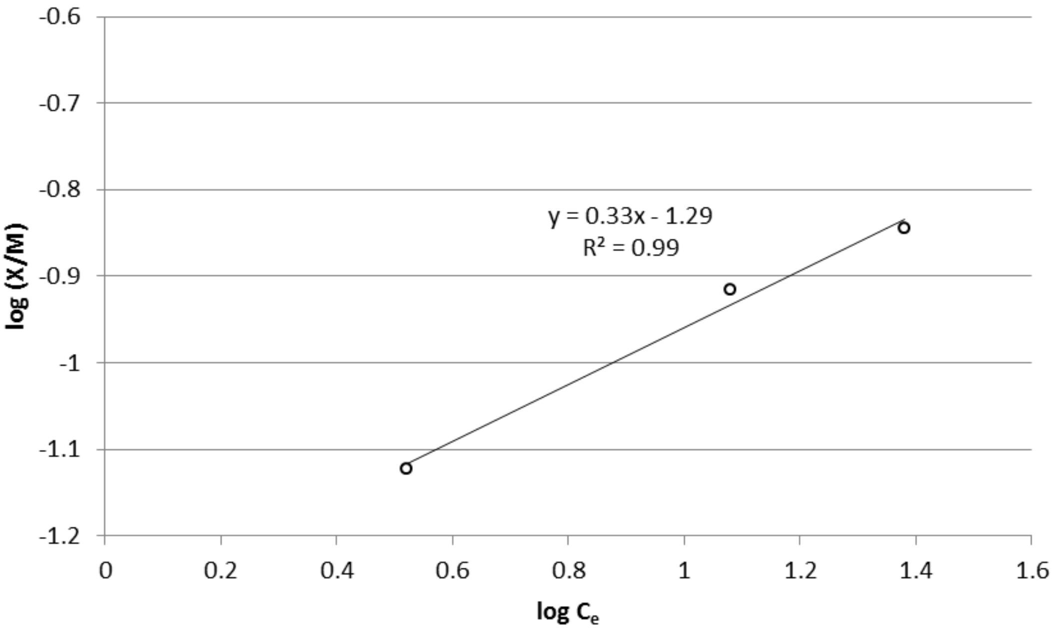


Figure 13. Fruendlich Isotherm of ammonia sorption to mulch. Ce is mg N/L, X is grams of ammonia adsorbed, and M is mass of mulch used.

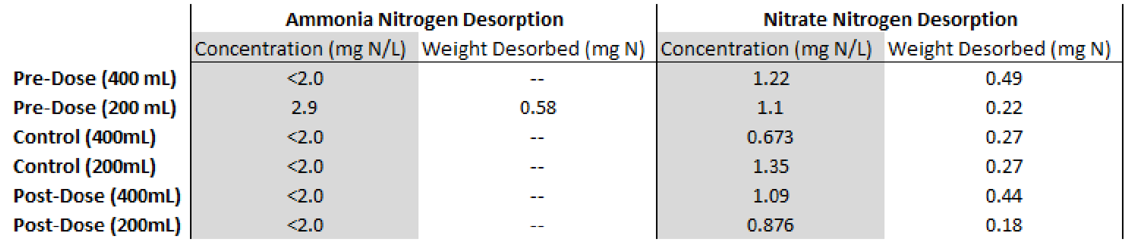
The results show that mulch readily adsorbs ammonia, while pea gravel appears to not adsorb ammonia at all. The concentrations of ammonia that were added to the mulch went from 15, 30, and 45 mg N/L to approximately 3.3, 12, 24 mg N/L, respectively. The pea gravel concentrations either remained constant or actually increased, which could be due to small amounts adsorbed to small particles within the pea gravel. The values obtained from the Fruendlich isotherm for the mulch are a K of 0.05 and 1/n of 0.33. This possibly explains the amount of ammonia removal experienced by the unaerated wetland cells. Once the ammonia is adsorbed to the mulch there is a possibility of biological activity occurring and converting the ammonia to nitrate. This nitrate would then be released back into the solution once the surface is rewetted. The mulch could also act as a storage reservoir for ammonia and possibly release ammonia upon chemical changes within the wastewater.

A desorption experiment was conducted to examine the amount of desorption occurring using actual wetland cell mulch. The mulch was taken from a unaerated wetland cell 1 in three different locations:

- The first two linear feet of the wetland cell immediately before a dose;
- the last two linear feet of the wetland cell; and
- the first two linear feet of the wetland cell immediately after a dose.

The samples were collected pre- and post-dose because it was hypothesized that the nitrogen make-up may be different. The pre-dose sample was thought to possibly contain higher concentrations of nitrate, while the post-dose sample was expected to contain higher concentrations of ammonia. The sample in the last two linear feet was hypothesized to be a control because it is not regularly wetted with wastewater. The first two linear feet of the wetland become totally wetted during each dose because the wastewater initially backs-up. The samples were placed in beakers and two different volumes of distilled water were added to each sample collected. The samples reacted for 24 hours with no atmospheric interchange and the results are in Table 14.

Table 14. Desorption ammonia and nitrate concentrations and weights for three wetland cell mulch samples.



	Ammonia Nitrogen Desorption		**Nitrate Nitrogen Desorption**	
	Concentration (mg N/L)	Weight Desorbed (mg N)	Concentration (mg N/L)	Weight Desorbed (mg N)
Pre-Dose (400 mL)	<2.0	--	1.22	0.49
Pre-Dose (200 mL)	2.9	0.58	1.1	0.22
Control (400mL)	<2.0	--	0.673	0.27
Control (200mL)	<2.0	--	1.35	0.27
Post-Dose (400mL)	<2.0	--	1.09	0.44
Post-Dose (200mL)	<2.0	--	0.876	0.18

The results show that there were small amounts of desorption of ammonia and nitrate. The detection limit of 2 mg N/L severely limited the analysis of ammonia desorption. The nitrate desorption showed that the two samples taken from the first two linear feet of the wetland released similar concentrations of nitrate, while the control sample taken from the last two linear feet of the wetland cell showed smaller amounts of desorption. This test revealed that the mulch may be acting as more of a storage reservoir, rather than biologically converting ammonia to nitrate. The ammonia appears to stay adsorbed fairly well because the sorption test proved that it is capable of storing high amounts of ammonia, but the desorption results show it does not release as much relative to the amount adsorbed in the lab.

5.5 Hydraulic Modeling

Effectively modeling of the hydraulics of a wetland is important to not only understand the fate and transport of pollutants, but it is also modeling nutrient removal within the wetland. A tracer study was performed to gain an understanding of the hydraulics of each wetland cell. The tracer curves can be seen in Figure 14 through Figure 20.

The results obtained from the tracer tests were what was expected, a time-delayed bell-shaped curve (Kadlec and Wallace, 2009). Irregularities of a second peak at day 8 are shown in all of the recovery concentrations with the peak height of each varying. This could be caused by a pocket of water moving at a different pace than the main flow or could also be the result of a sampling error. From the recovery curves a mass recovery can be determined from Equation 2-2 in Chapter 2 and compared to the initial mass to assure a valid tracer test. The tracer detention time (τ) can also be determined using

Equation 2-3 from Chapter 2. The tracer detention time along with the peak detention time, determined from the curves, can be used to determine an N, number of tanks-in-series. This N value will later be used to model nitrogen removal. These values are in Table 15.

Tracer recovery percentages showed varying results of nearly 100% recovery and some considerably lower or higher than 100% recovery. This variability could be, at least partially, explained by the dosing method because only three wetland cells could be dosed at once due to the size of the dosing reservoir. This could cause, with poor mixing, one wetland cell to be dosed a larger amount than another wetland cell. The only wetland cell to be dosed individually was the planted/aerated wetland cell 8 and showed approximately 100% recovery. Using these results and the nominal detention time, τ_n, a volumetric efficiency can be determined using

from Chapter 2. The resulting volumetric efficiencies are in Table 16.

From the mean detention times and the volumetric efficiencies the planted/aerated wetland cell 6 has the highest detention time and also the highest volumetric efficiency. This cell also has the highest treatment efficiency and a 25% higher volumetric efficiency compared to the duplicate of this cell, which could help explain the significant difference between the two cells in terms of treatment. The volumetric efficiency of the wetland cells are on the low range of expected volumetric efficiencies. For typical subsurface flow wetlands Kadlec and Wallace (2009) reported values ranging from 0.28 to 1.08, with the majority of the values falling between 0.75 and 1.02. The volumetric efficiency reflects the fraction of the volume within a wetland that is being utilized. Higher volumetric efficiencies can correlate to higher treatment efficiencies as well, mainly due to the extended retention time. The volumetric efficiency can be affected by biomass, bypassing, and poor wetland topography (Kadlec and Wallace, 2009).

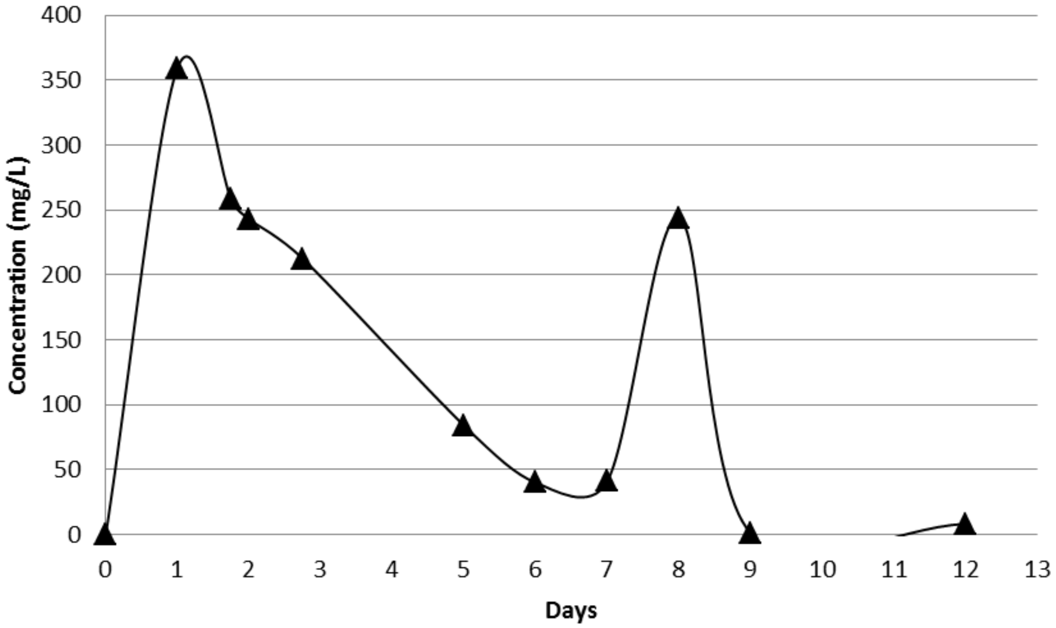


Figure 14. Effluent bromide concentration vs. time for unplanted/unaerated wetland cell 1, September 2011.

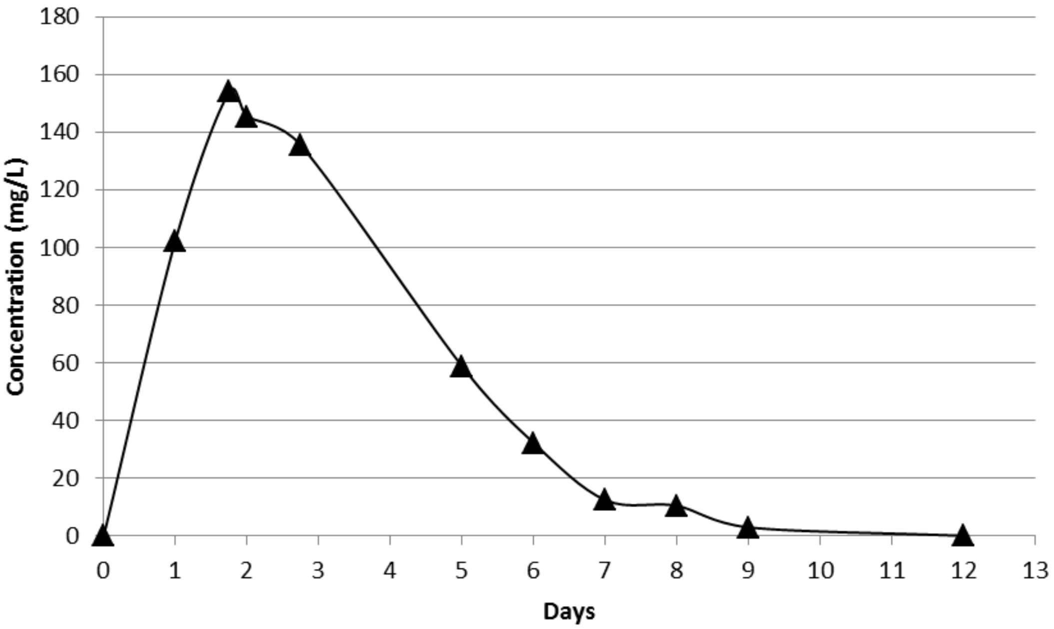


Figure 15. Effluent bromide concentration vs. time for unplanted/aerated wetland cell 2, September 2011.

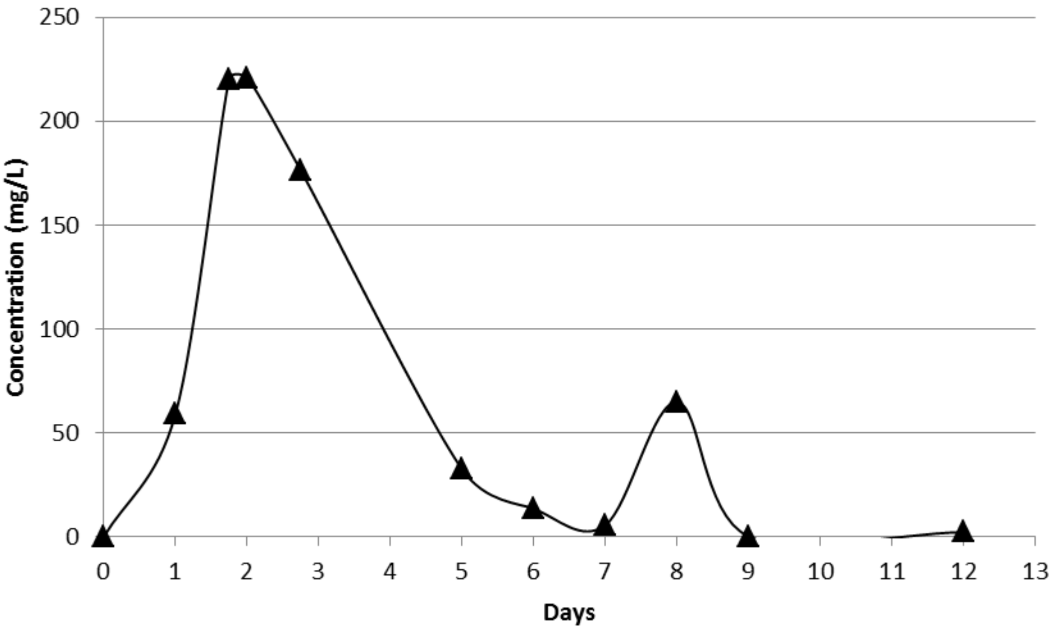


Figure 16. Effluent bromide concentration vs. time for unplanted/unaerated wetland cell 3, September 2011.

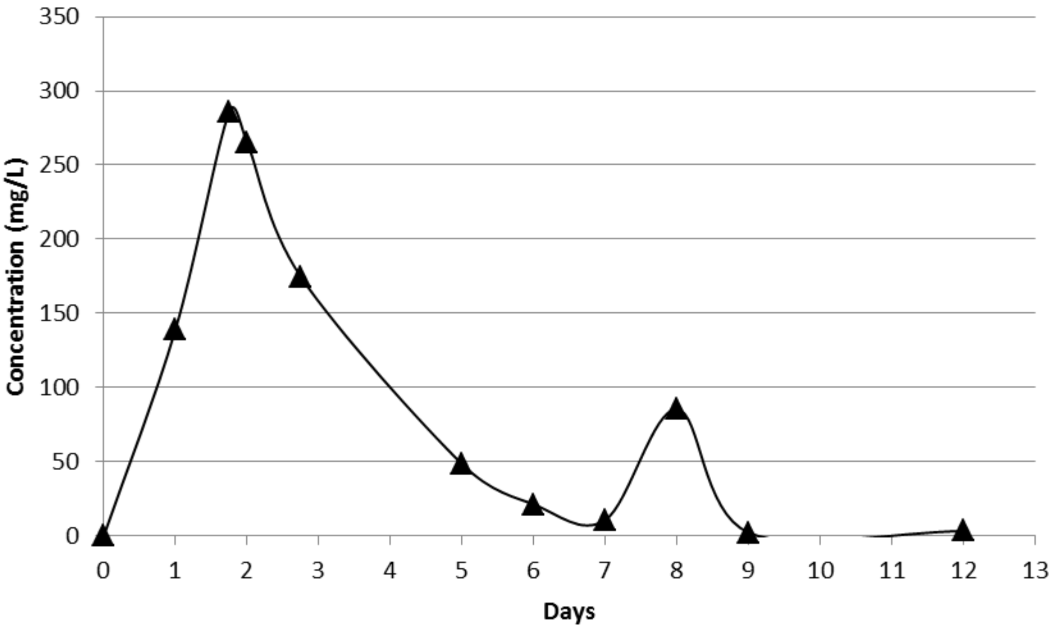


Figure 17. Effluent bromide concentration vs. time for planted/unaerated wetland cell 5, September 2011.

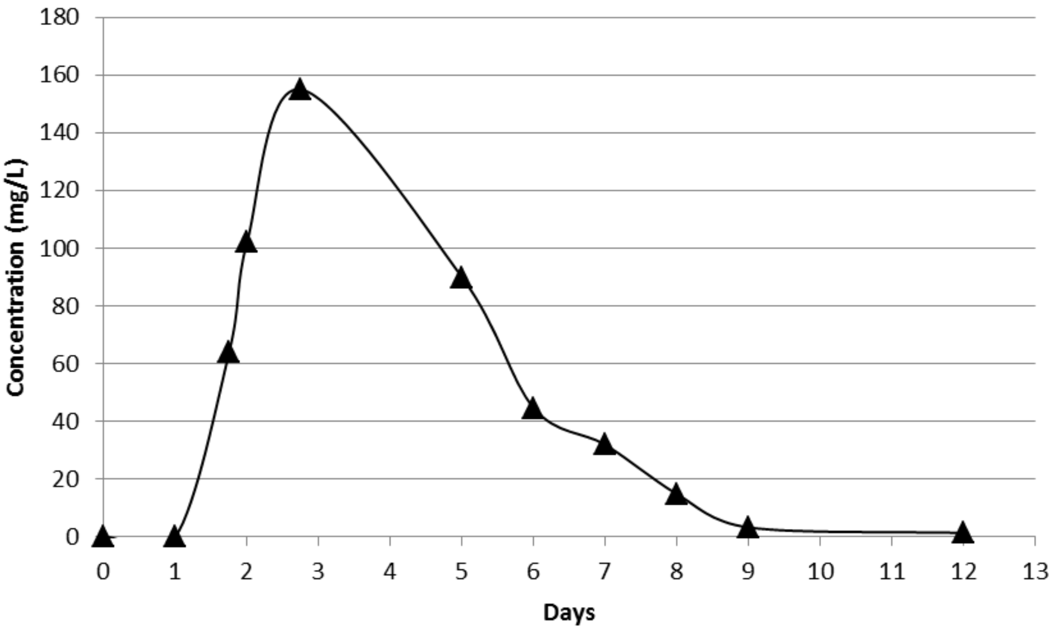


Figure 18. Effluent bromide concentration vs. time for planted/aerated wetland cell 6, September 2011.

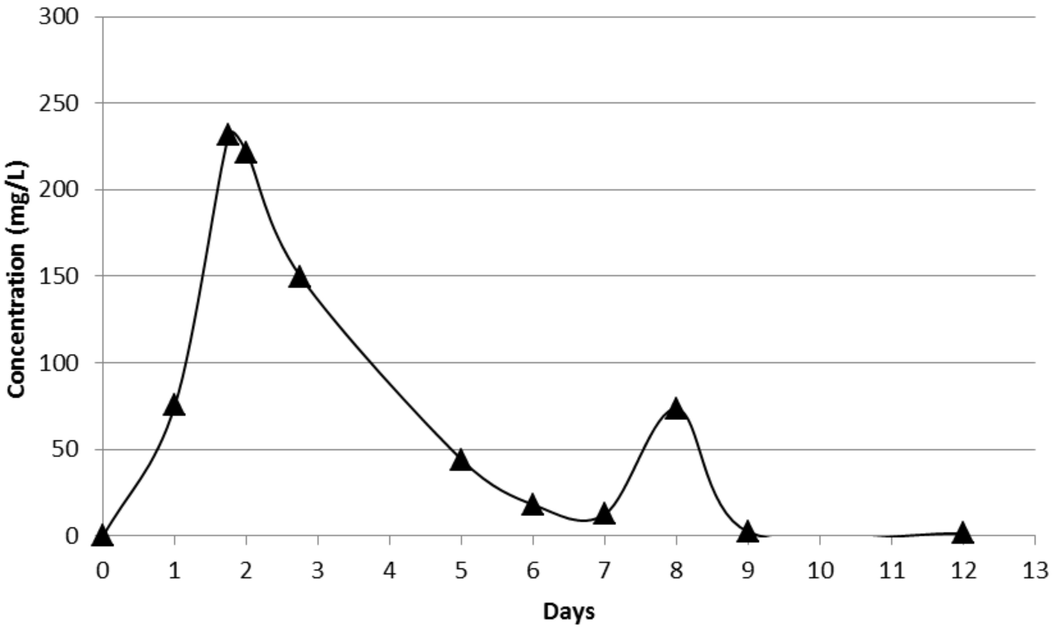


Figure 19. Effluent bromide concentration vs. time for planted/unaerated wetland cell 7, September 2011.

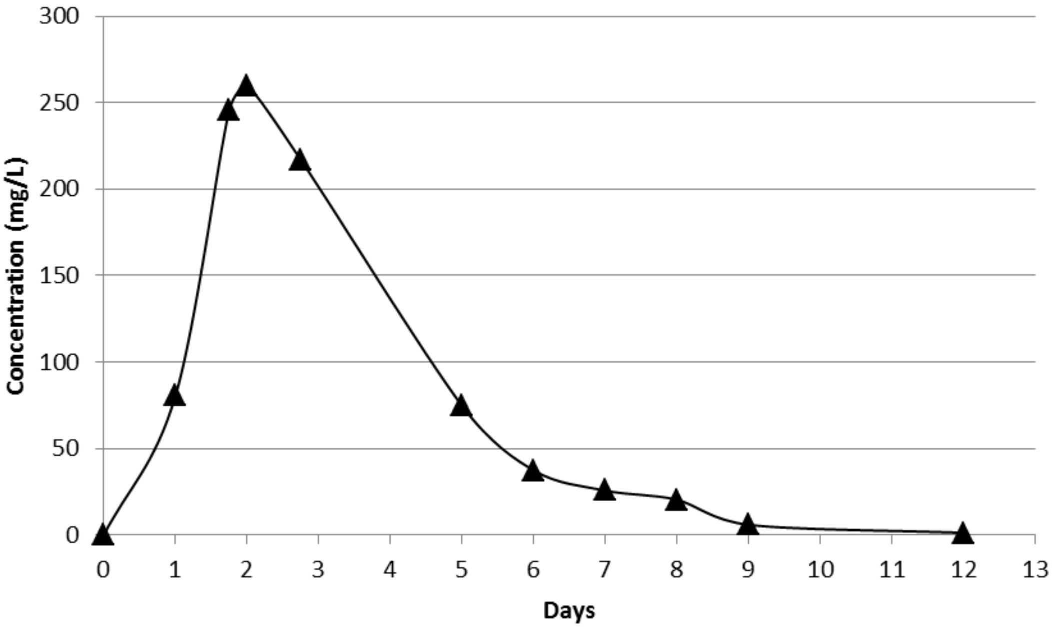


Figure 20. Effluent bromide concentration vs. time for planted/aerated wetland cell 8, September 2011.

Table 15. Tracer test recovery percentages, mean and peak detention times, and number

Wetland Cell	Mass Recovery Percent	τ (days)	τ_{peak} (days)	N
Unplanted/Unaerated (1)	180.4	3.80	1.20	1.46
Unplanted/Aerated (2)	77.5	3.13	1.80	2.36
Unplanted/Unaerated (3)	81.3	3.21	1.90	2.45
Planted/Unaerated (5)	104.4	3.15	1.80	2.33
Planted/Aerated (6)	67.6	4.33	2.80	2.84
Planted/Unaerated (7)	84.4	3.37	1.80	2.15
Planted/Aerated (8)	100.5	3.25	2.00	2.59

Table 16. Volumetric efficiencies, e_v, for each wetland cell.

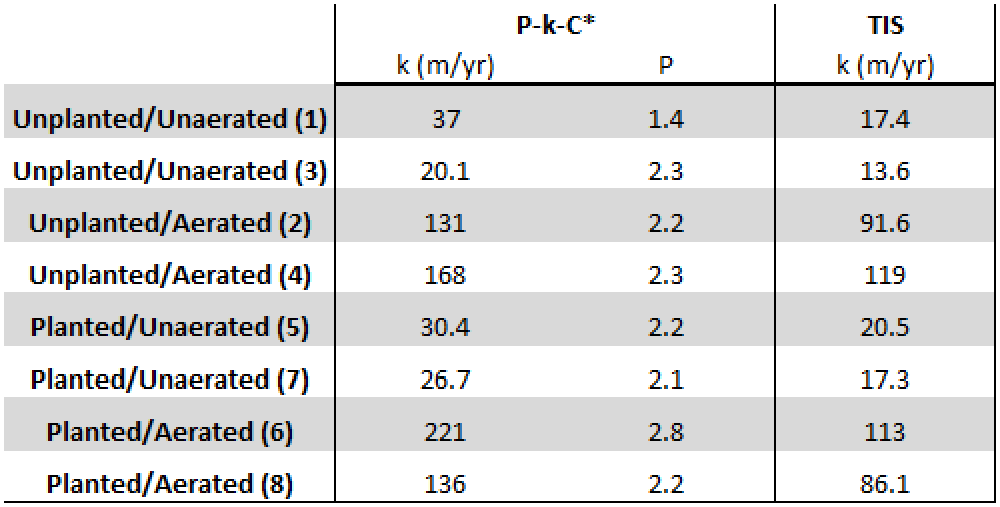
Wetland Cell	Volumetric Efficiency, e_v
Unplanted/Unaerated (1)	0.53
Unplanted/Aerated (2)	0.42
Unplanted/Unaerated (3)	0.43
Planted/Unaerated (5)	0.43
Planted/Aerated (6)	0.57
Planted/Unaerated (7)	0.46
Planted/Aerated (8)	0.43

5.6 Nitrogen Modeling

5.6.1 Ammonia Modeling

The ability to effectively predict the effluent concentrations is important for the design of wetlands. In the past the main model was the tanks-in-series (TIS) model, but recently the P-k-C* model is considered the best approach for predicting removal. For this study both models were used to compare the rate coefficients obtained. The background concentration, C*, is the constant assumed using the P-k-C* model after following the general rules presented in Chapter 2. For ammonia removal Kadlec and Wallace (2009) assumed a zero background concentration and this will also be used for ease of comparison with other values. Table 17 shows the values obtained for both models and Figure 21 through Figure 28 are graphs of the predicted effluent concentrations with the actual effluent concentrations. Ammonia data are from Dec. 2010 to Mar. 2012 with unplanted/aerated wetland cell 2 and 4 consisting of less data (both wetland cells had periods of no operation; cell 2 had a leak and cell 4 had possible clogging).

Table 17. Rate cofficients and P values for the P-k-C* and TIS models of ammonia removal.



	P-k-C*		**TIS**
	k (m/yr)	P	k (m/yr)
Unplanted/Unaerated (1)	37	1.4	17.4
Unplanted/Unaerated (3)	20.1	2.3	13.6
Unplanted/Aerated (2)	131	2.2	91.6
Unplanted/Aerated (4)	168	2.3	119
Planted/Unaerated (5)	30.4	2.2	20.5
Planted/Unaerated (7)	26.7	2.1	17.3
Planted/Aerated (6)	221	2.8	113
Planted/Aerated (8)	136	2.2	86.1

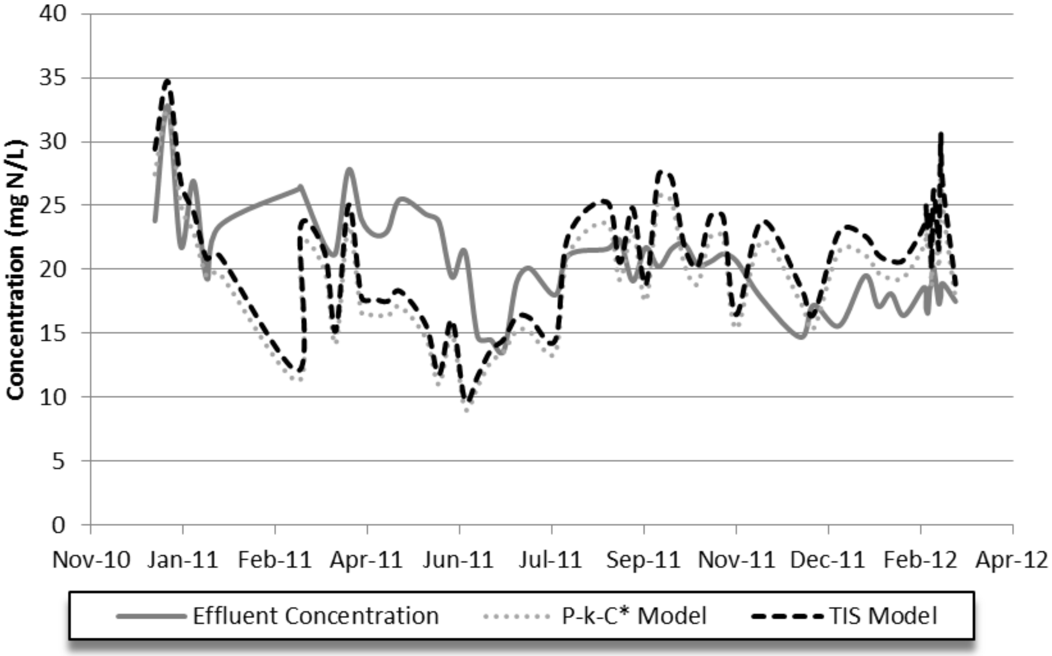


Figure 21. Actual ammonia concentrations compared to model predicted concentrations for unplanted/unaerated 1.

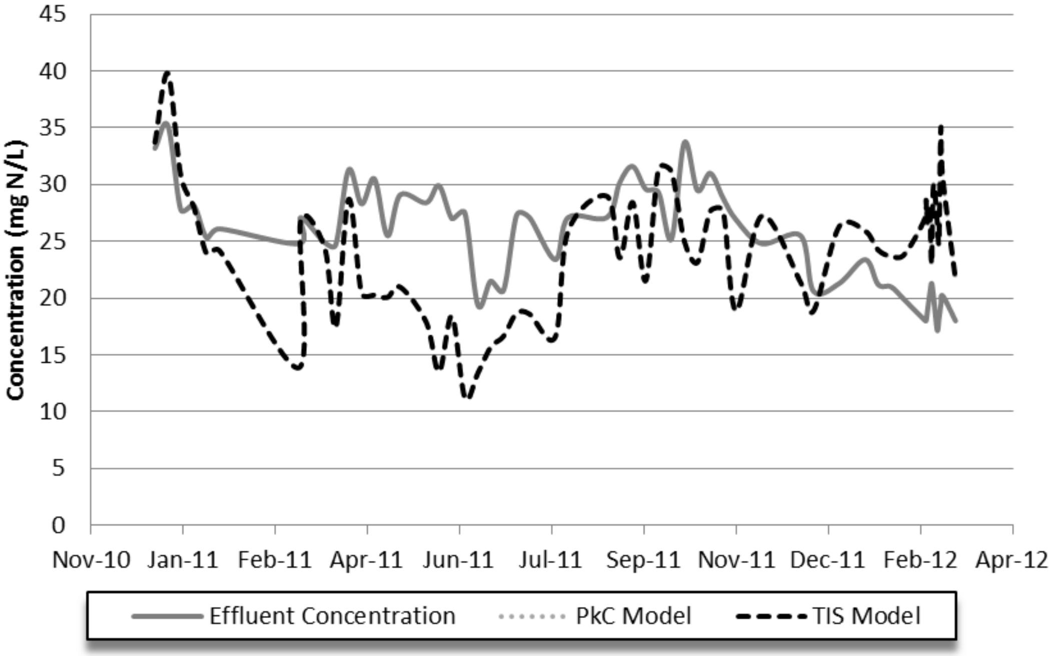


Figure 22. Actual ammonia concentrations compared to model predicted concentrations for unplanted/unaerated 3.

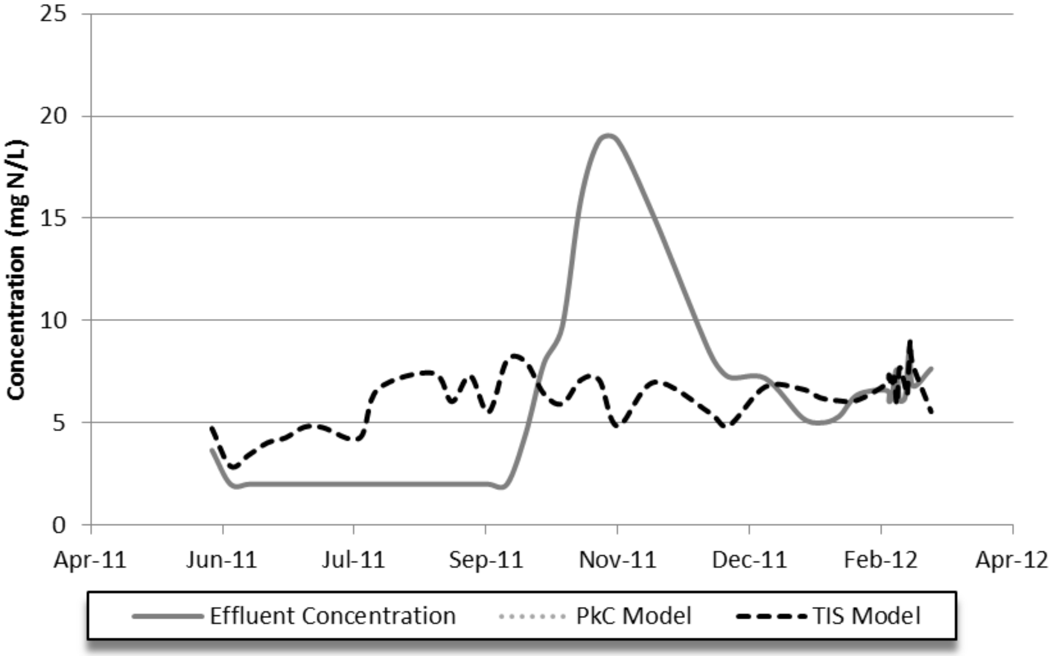


Figure 23. Actual ammonia concentrations compared to model predictions for unplanted/aerated wetland cell 2.

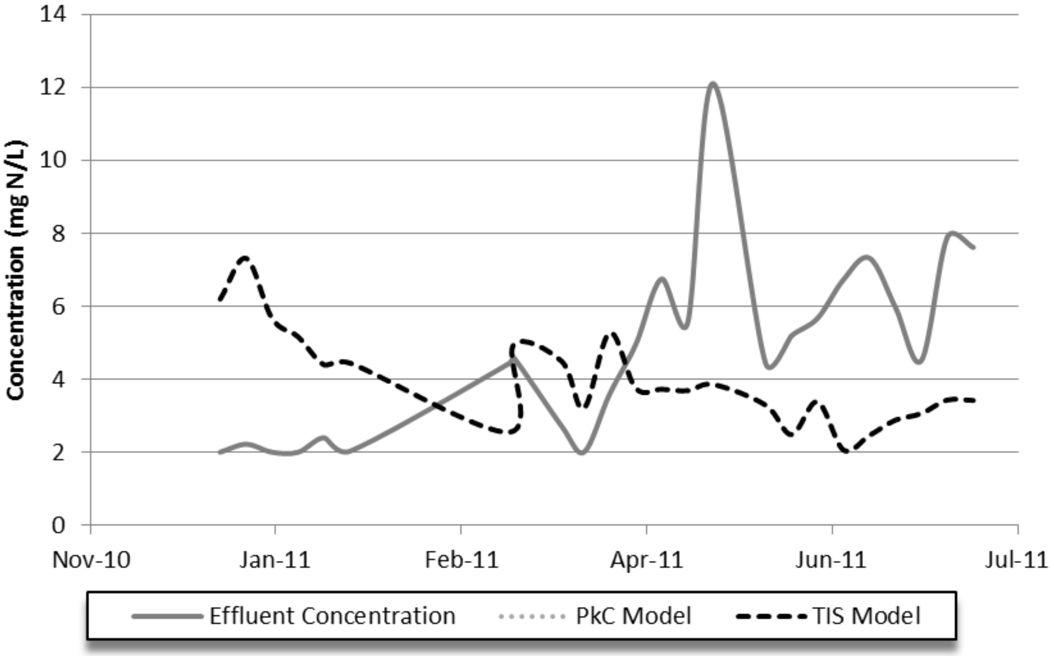


Figure 24. Actual ammonia concentrations compared to model predictions for unplanted/aerated wetland cell 4.

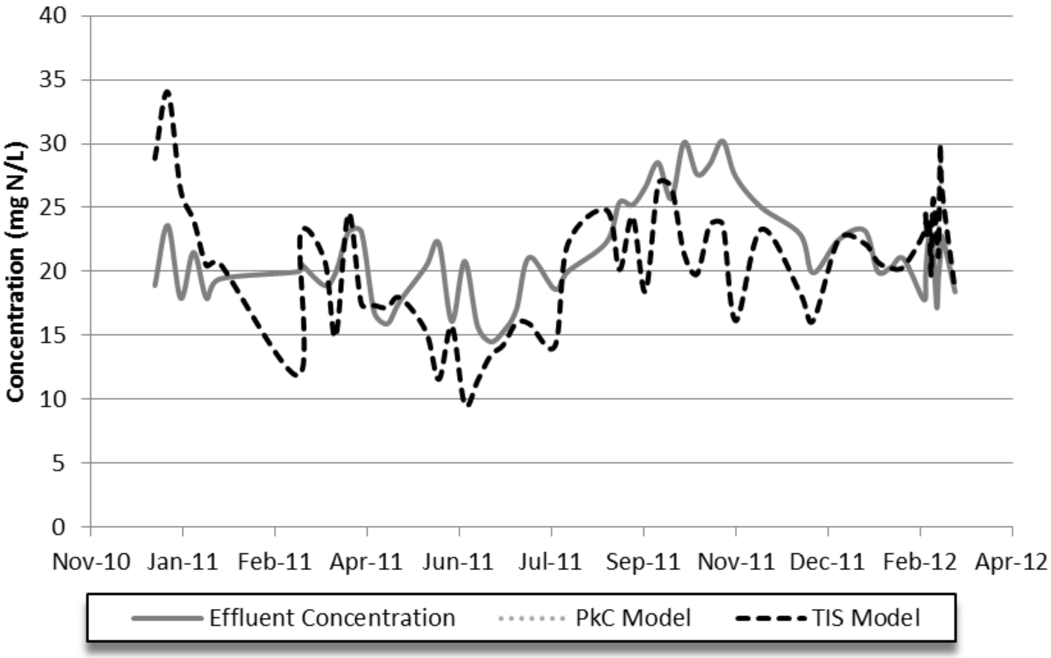


Figure 25. Actual ammonia concentrations compared to model predictions for planted/aerated wetland cell 5.

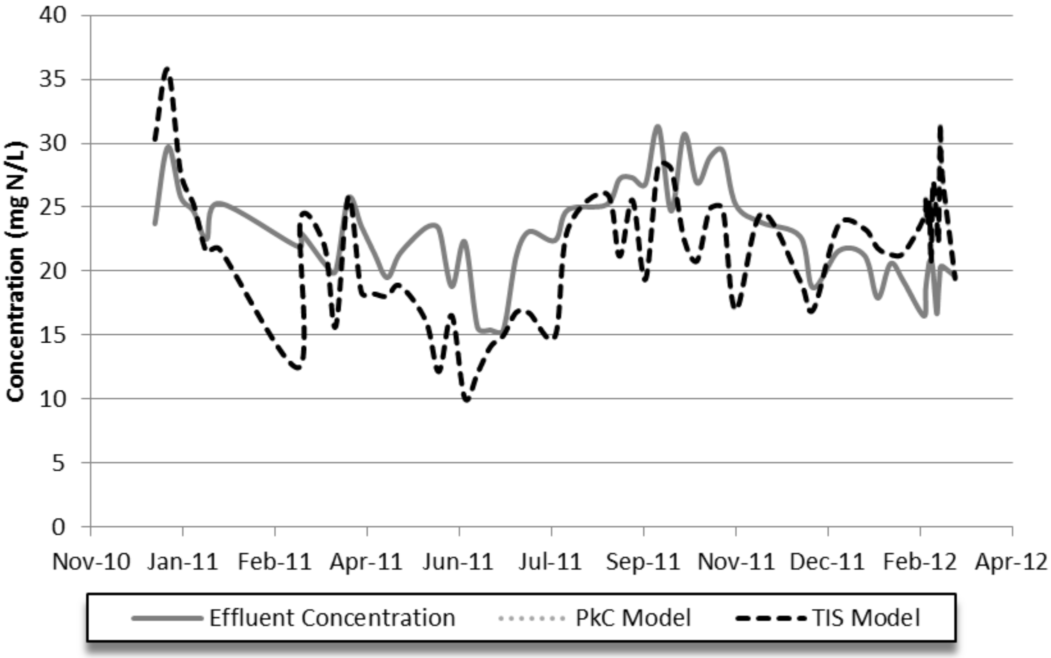


Figure 26. Actual ammonia concentrations compared to model predictions for planted/unaerated wetland cell 7.

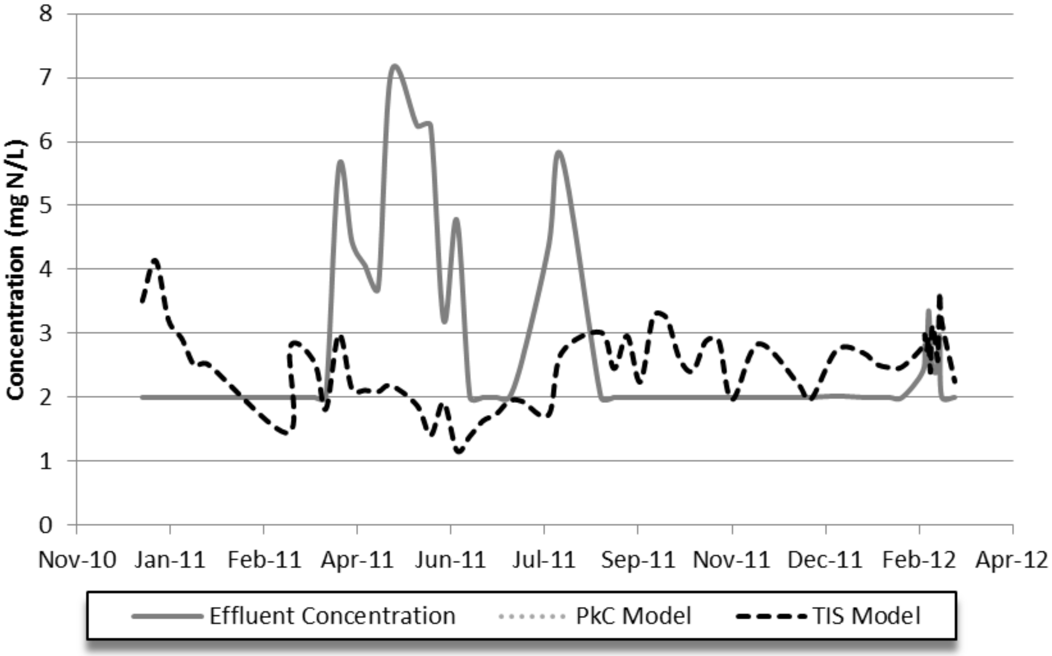


Figure 27. Actual ammonia concentrations compared to model predicted concentrations for planted/aerated 6.

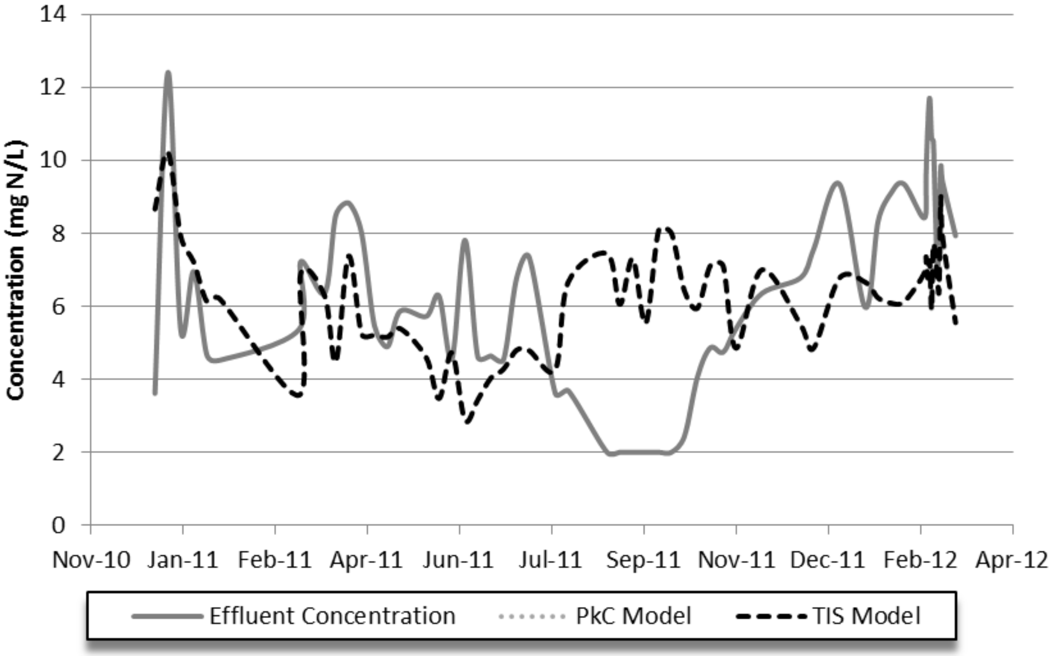


Figure 28. Actual ammonia concentrations compared to model predicted concentrations for planted/aerated 8.

The rate coefficients using the P-k-C* model are on average 37% larger than the k values obtained using the TIS model. The k-values obtained for the aerated systems are much larger than the values obtained from the unaerated wetland cells. There appears to be no advantage in terms of k values when comparing the unplanted/aerated cells to the planted/aerated cells, showing that vegetation appears to have no effect on the removal of ammonia. When comparing the P values to N values determined earlier, all of the P values are lower or near N values, which is expected (Kadlec and Wallace, 2009). Both models predict essentially the same effluent concentrations; the graphing of both models is identical. Both models give a fairly accurate depiction of the effluent concentration for the unaerated wetland cells. Both models seem to have difficulty predicting the effluent concentrations for the aerated wetland cells, particularly the highs and lows. If the influent concentrations were plotted on the same graphs as the models, the models essentially mask the influent concentration. This is not surprising considering the only value that changes within each model is the influent concentration. A more effective model for aerated systems seems to be in order to assist in predicting the effects of temperature and aeration.

One trend that is easily seen from both models and the actual concentrations are the slight rise in effluent concentrations during the winter months. The wetland cells were shut down during February 2011, which was an extremely cold month with a record snow storm. All of the wetlands were able to survive the month of February 2011 without freezing even when not receiving daily dosages (wetlands were shut down because of pump problems and the data in the graphs was run continuously when displayed). The months surrounding February 2011 were still relatively cold and it is apparent especially with the unaerated wetlands that treatment efficiency decreases. The aerated wetlands appear to minimize decreases in treatment efficiency through the colder months.

5.6.2 Total Nitrogen Modeling

The same approach for ammonia modeling was used to model total nitrogen, with the exception of the background concentration. The background concentration, C*, was the constant assumed using the P-k-C* model after following the general rules presented in Chapter 2. For TN removal Kadlec and Wallace (2009) assumed a 1 mg N/L background concentration for TN and this will also be used for ease of comparison with other values. Table 18 shows the values obtained for both models and Figure 29 through Figure 36 display graphs of the predicted effluent concentrations with the actual effluent concentrations. TN data are from Jun 2011 to Mar. 2012 with unplanted/aerated wetland cell 2 and 4 consisting of less data (both wetland cells had periods of no operation; cell 2 had a leak and cell 4 had possible clogging). There are fewer data for TN than ammonia because of TN testing complications.

Table 18. Rates and P values for the P-k-C* and TIS models of total nitrogen removal.

	P-k-C*		**TIS**
	k (m/yr)	P	k (m/yr)
Unplanted/Unaerated (1)	61.1	1.5	34.2
Unplanted/Unaerated (3)	37.7	2.1	25.9
Unplanted/Aerated (2)	109	2.1	80.2
Unplanted/Aerated (4)	93.2	1.8	67.0
Planted/Unaerated (5)	41.4	2.2	28.8
Planted/Unaerated (7)	41.4	2.1	27.6
Planted/Aerated (6)	129	2.3	66.0
Planted/Aerated (8)	100	2.1	65.8

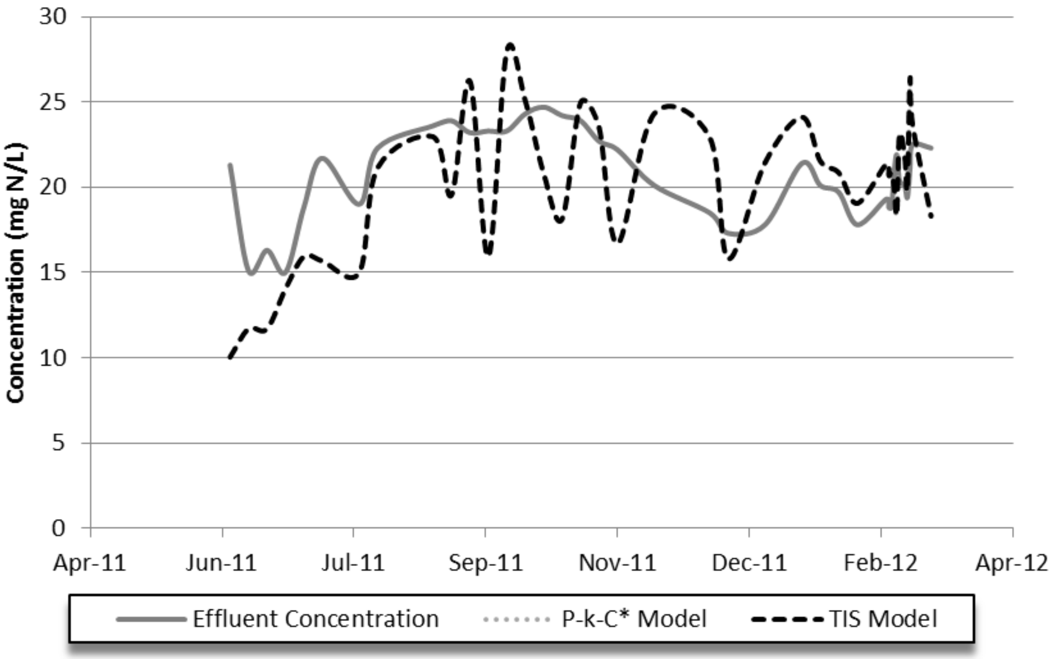


Figure 29. Actual total nitrogen concentrations compared to model predicted concentrations for unplanted/unaerated 1.

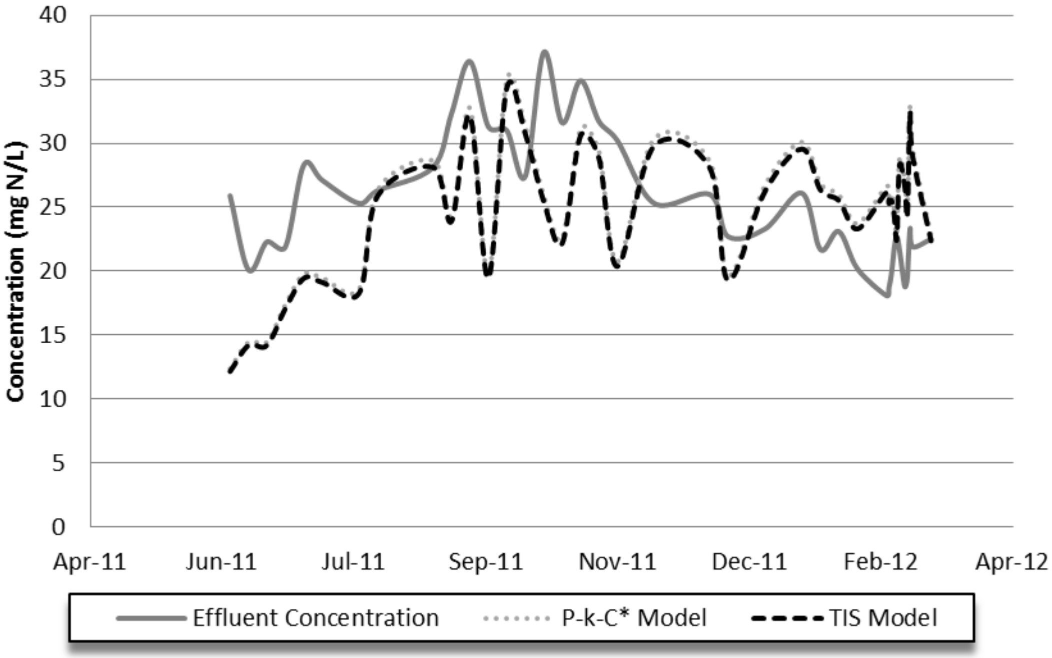


Figure 30. Actual total nitrogen concentrations compared to model predictions for unplanted/unaerated wetland cell 3.

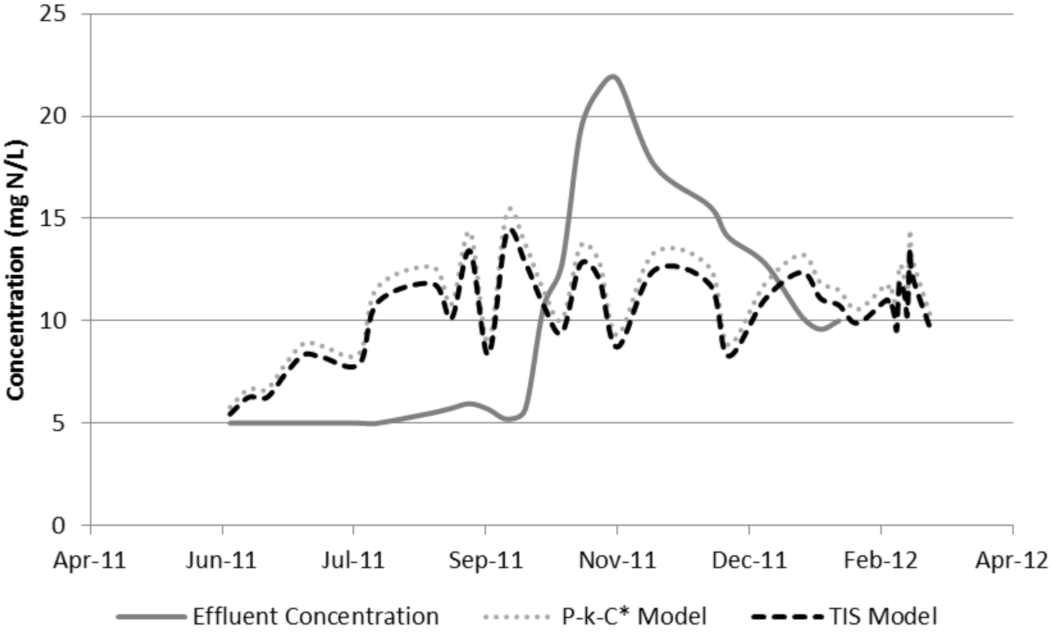


Figure 31. Actual total nitrogen concentrations compared to model predictions for unplanted/aerated wetland cell 2.

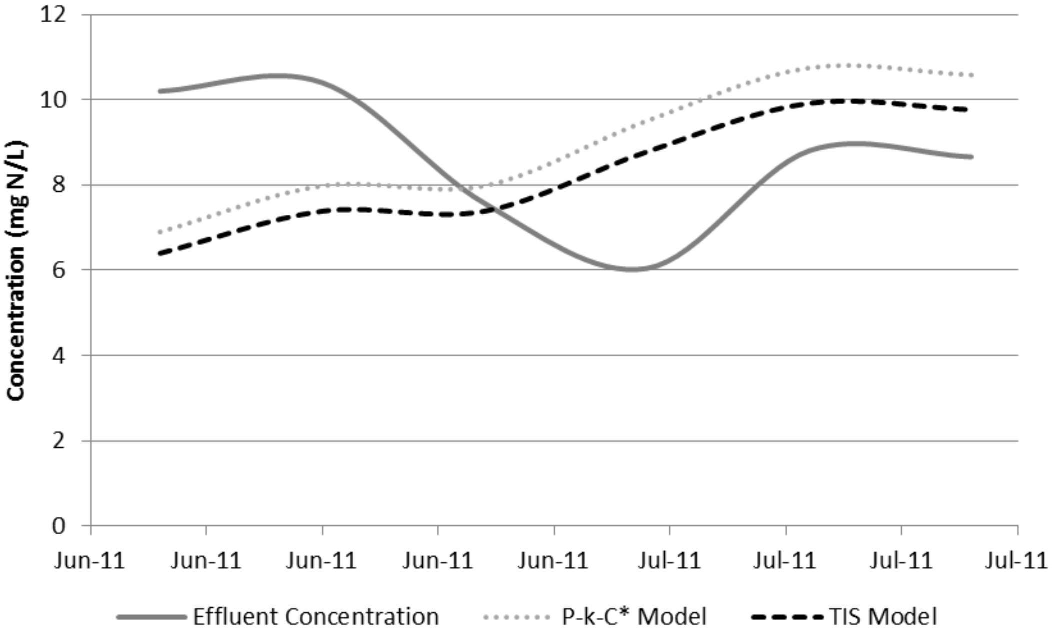


Figure 32. Actual total nitrogen concentrations compared to model predictions for unplanted/aerated wetland cell 4.

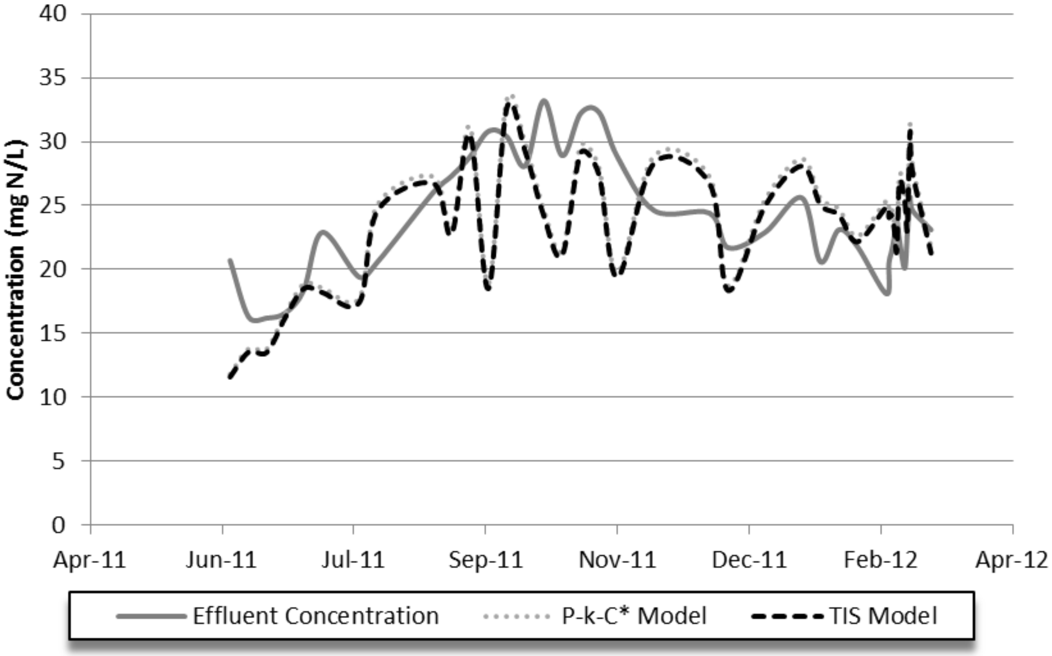


Figure 33. Actual total nitrogen concentrations compared to model predictions for planted/unaerated wetland cell 5.

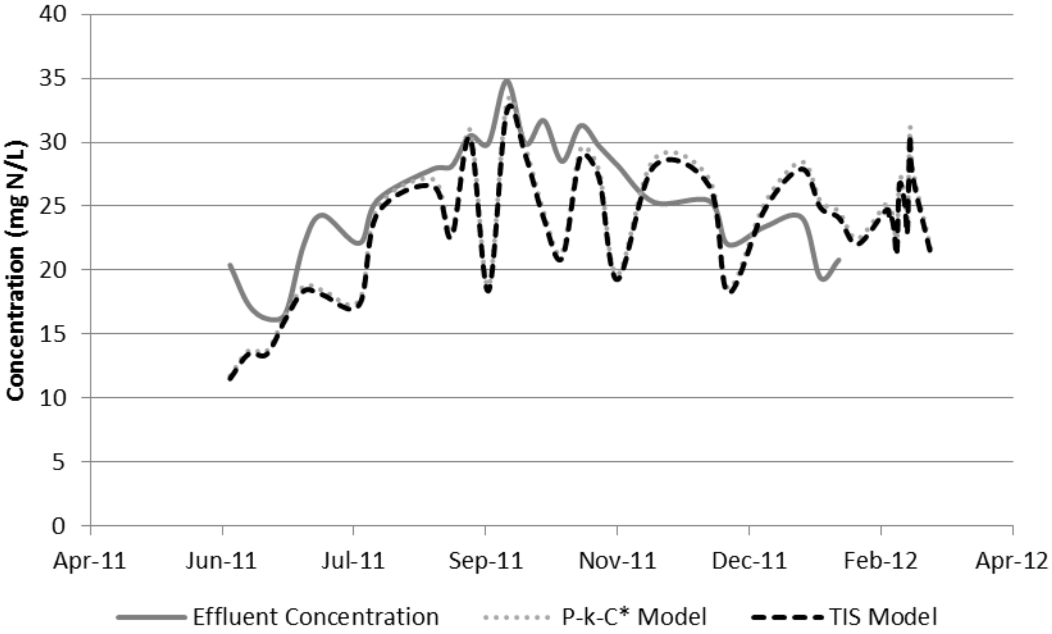


Figure 34. Actual total nitrogen concentrations compared to model predictions for planted/unaerated wetland cell 7.

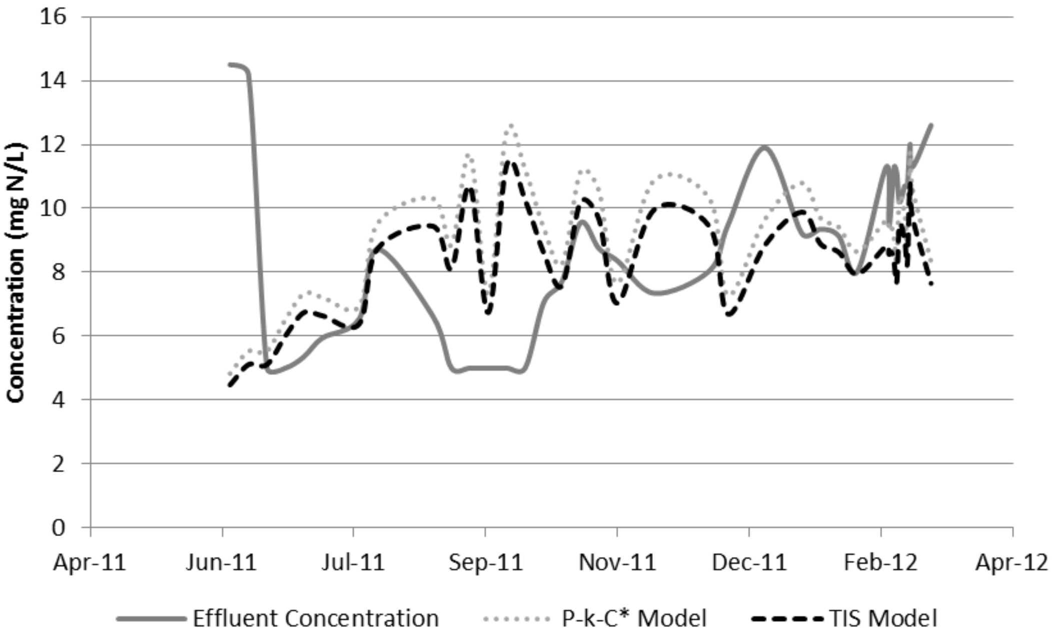


Figure 35. Actual total nitrogen concentrations compared to model predicted concentrations for planted/aerated 6.

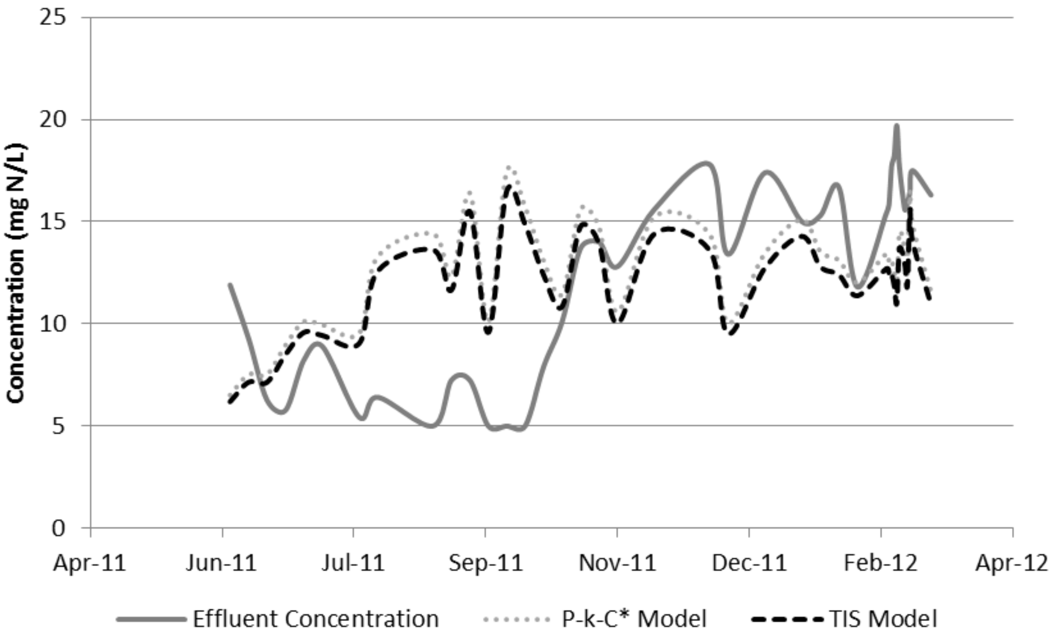


Figure 36. Actual total nitrogen concentrations compared to model predictions for planted/aerated wetland cell 8.

Results for TN modeling are similar to those for ammonia in that the k values for the TIS model are lower than those obtained using the P-k-C* model. Both models are again inadequate for predicting the high and low effluent concentrations. There again appears to be little if any differences in the k-values when comparing planted and unplanted wetland cells.

The trend of decreasing treatment efficiency that was seen with the ammonia models is less apparent with the TN models. There is still a noticeable increase in the concentration through the winter months, but there are only data available from the 2011-2012 winter months.

5.7 Temperature

The purpose of the mulch layer on top of the wetlands is to enable treatment to occur throughout the year in cold climates. Ambient air and water temperature data were collected beginning in mid-August 2011. The water temperature follows the trend of the ambient air temperature, but always remains above 0°C. Figure 37 shows the ambient air temperature and water temperature data from the planted/aerated wetland cell 6. All of the wetland cells follow the same general trend with little difference. Data from a cold winter that could possibly show lower ambient air temperatures to compare with water temperatures could not be collected because of the record warm winter experienced in 2011-2012.

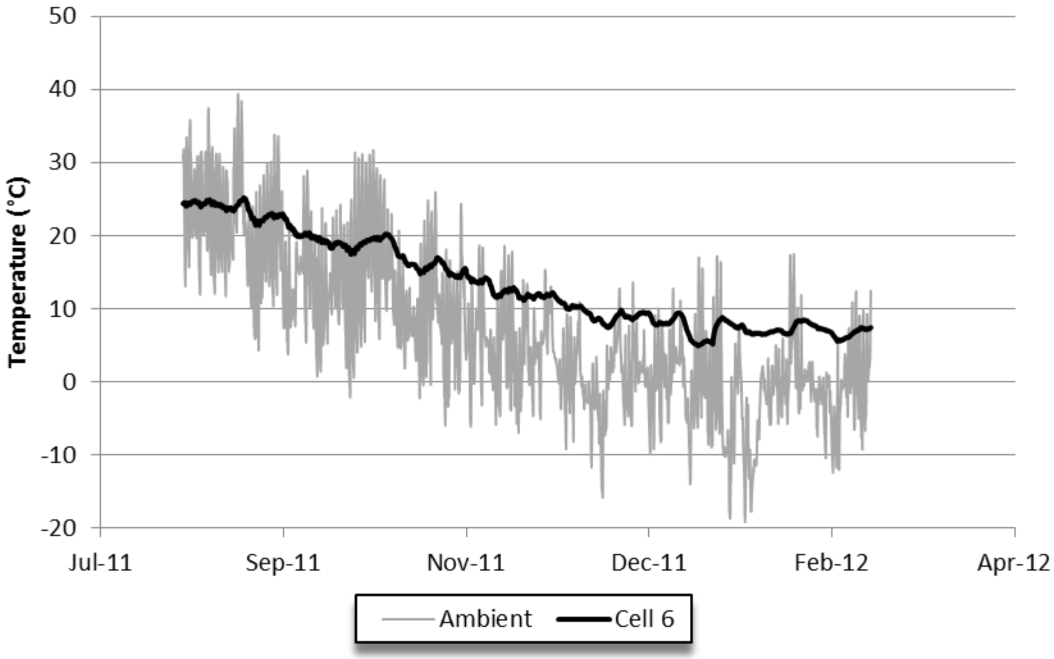


Figure 37. Ambient air and water temperature for planted/aerated wetland cell 6.

5.8 Energy Analysis

Power requirement is a major concern when considering treatment technologies. A study by Austin and Nivala (2009) determined aerated subsurface flow wetlands used approximately half of the power compared to a mechanical activated-sludge treatment system. A traditional activated-sludge system uses approximately 0.88 kWh/m^3-d, while the aerated subsurface flow wetland required 0.49 kWh/m^3-d for identical wastewater flows (Austin and Nivala, 2009). These power requirements were only determined for aeration and recycle pumping. Here we consider only aeration as a power requirement because other pumping would not be required. The blower used was a Pondmaster AP-

100 blower. Our wetland cells use 0.44 kWh/m^3-d, which is comparable to the Austin and Nivala (2009) study. Calculations can be seen in the Appendix.

CHAPTER 6
SUMMARY AND CONCLUSION

The purpose of this research was to assess the ability of subsurface flow wetlands, with aeration and vegetation, to remove nitrogen in cold weather climates. Aeration was shown to enhance the wetland cell's ability to remove not only nitrogen but also CBOD, COD, and phosphorus (retention) more effectively. Average influent total nitrogen concentrations of 45.9 mg N/L were reduced to approximately 10 mg N/L within the aerated wetlands. Nitrate formation was observed throughout all months of treatment showing that nitrification was occurring. Effluent nitrate concentrations from the aerated wetlands were never higher than 10 mg N/L, with the highest average concentration of 6.6 mg N/L. This shows that not only was nitrification occurring but denitrification was as well. Nitrate concentrations appeared to slightly increase during colder temperatures, but extremely low temperatures were not experienced to show possible significance between warm and cold temperatures.

Ammonia removal efficiencies for the aerated wetland cells ranged from 80% to 95%, while the unaerated wetland cells had efficiencies ranging from 39% to 45%. For some unaerated wetland cells ammonia removal was above 50% at times, so adsorption tests were performed to identify any ammonia sinks. Ammonia adsorbed to mulch with a K of 5.16×10^{-5} and 1/n of 0.33 using the Fruendlich Isotherm. The pea gravel showed minimal sorption and actually showed slightly higher concentrations in some cases than the original concentration. Ammonia removal showed no significance when compared over three different ranges of temperatures. There was also high correlation between ammonia mass removal rates and mass loading rates showing that temperature may play a minimal role in transformation.

Total nitrogen removal efficiencies mirrored ammonia removal efficiencies because ammonia makes up a large fraction of the total nitrogen. The removal efficiencies were slightly lower than ammonia removal efficiencies within the aerated wetlands because of nitrate concentrations. A significant difference ($p < 0.05$) was detected when comparing the unaerated to the aerated wetland cells, while there was no significant difference detected between the planted and unplanted wetland cells.

A tracer test was performed in September 2011 to assess the hydraulics of each wetland cell and to help with nutrient modeling. The hydraulic retention times ranged from 3.13 to 4.33 days and the tanks-in-series for each wetland ranged from 1.46 to 2.84. Planted/aerated wetland cell 6 had the longest retention time and the most tanks-in-series also, which could explain the significantly ($p<0.05$) higher removals compared to its duplicate, planted/aerated wetland cell 8.

The wetland cells were modeled for both ammonia and total nitrogen removal using both the TIS model and the PkC* model. The aerated wetland cells had k values (PkC* model) for ammonia ranging from 131.1 to 221.2 m/d, while the unaerated cells had values ranging from 20.4 to 36.7 m/d. The k values (PkC* model) of the aerated wetland cells for total nitrogen ranged from 100.3 to 129.1 m/d, while the unaertaed wetland cells ranged from 41.41 to 61.12 m/d. The lower k values of the aerated wetland cells for total nitrogen compared to ammonia are expected because of the formation of nitrate without complete denitrification. The unaerated wetland cells also showed higher than expected ammonia removals. Both models appear to effectively predict effluent concentrations for the unaerated wetland cells but the models are not as effective when predicting the aerated wetland cell concentrations.

Contaminants of concern other than nitrogen species were also measured throughout the study. CBOD removal efficiencies ranged from 88% to above 98%, with the aerated wetland cells showing higher consistency throughout the winter months. Total suspended solids were consistently low throughout the study with no apparent difference between aerated and unaerated wetland cells; removal efficiencies above 94% were achieved by all wetland cells. Phosphorus retentions ranged from 53% to 74% for the aerated wetland cells, while the unaerated wetland cells had retentions ranging from 12% to 23%.

CHAPTER 7

ENGINEERING SIGNIFICANCE AND SUGGESTIONS FOR FUTURE RESEARCH

The research presented in this thesis supports the idea that aerated subsurface flow wetlands are a viable option for nitrogen removal in cold climates. Data clearly show that aerated wetlands, with or without vegetation, provide nitrogen transformation that results in removal. The insulation layer has proven to adequately provide for nitrogen removal in a cold weather climate. This type of wetland has also proven to effectively remove COD, CBOD, TSS, and TN from a wastewater stream. The wetland cells have shown the ability to produce quality effluent and at lower power requirements than conventional activated sludge systems.

With all the research that has been done there is still a considerable amount of work to do. Recommendations for the future of this project and other aerated subsurface flow wetlands include:

1. Collect data from colder temperatures to adequately show nitrogen removal. Provide modeling parameters specific to temperature range to show any differences.
2. Collect samples from various points along the length and width of the wetland cells to determine when and where transformations are occurring.
3. Once 2) has been adequately performed change aeration cycling to provide most efficient use and further examine the when and where of transformations.

4. Once 2) and 3) have been performed change retention times to experiment with flows that can or cannot be handled and to assess how this again effects the when and where of transformations.
5. Find a method to effectively measure a dissolved oxygen concentration fluctuations throughout the wetland cells during the aeration and nonaeration cycles.
6. Monitor phosphorus retention and quantify the capacity of wetland cells with and without aeration or vegetation.
7. Provide accurate and robust measuring of the water cycle for the wetland cells to further understanding of removal efficiency.

APPENDIX

Information:

100 W Pondmaster Air Pump

12 hr/d aeration

1.03m^3/d (all four aerated wetlands)

25-30 scfh = 0.5 scfm = 2 scfm (all four aerated wetlands)

5.3 scfm Pondmaster Air Pump maximum supply

Calculations:

2 scfm/5.3 scfm = 0.377 (fraction used)

(100 W)*(12 hr/d)/(1.03 m^3/d) = 1165 W-hr/m^3 = 1.165 kWh/m^3

(1.165 kWh/m^3)*(0.377) = **0.44 kWh/m^3**

REFERENCES

"Approved General-Purpose Methods | CWA Methods | US EPA." *Home | Water | US EPA*. 25 Jan. 2012. Web. 26 Jan. 2012. <http://water.epa.gov/scitech/methods/cwa/methods_index.cfm>.

Austin, David, and Jaime Nivala. "Energy Requirements for Nitrification and Biological Nitrogen Removal in Engineered Wetlands." *Ecological Engineering* 35.2 (2009): 184-92. Print.

Crites R., Tchobanoglous G. (1998) Small and Decentralized Wastewater Management Systems. McGraw-Hill: New York.

"Design Guidance Documents." *Iowa Department of Natural Resources*. Web. 24 Feb. 2012. <http://www.iowadnr.gov/InsideDNR/RegulatoryWater/WastewaterConstruction/DesignGuidanceDocuments.aspx>.

"Ecological Design." *Gaia Education*. Global Ecovillage Network. Web. 20 Feb. 2012. <http://www.selba.org/EngTaster/Ecological/Water/Denitrification.html>.

Kadlec, Robert H., and Scott D. Wallace. *Treatment Wetlands*. Boca Raton, FL: CRC, 2009. Print.

Karathanasis, A.d., C.l. Potter, and M.s. Coyne. "Vegetation Effects on Fecal Bacteria, BOD, and Suspended Solid Removal in Constructed Wetlands Treating Domestic Wastewater." *Ecological Engineering* 20.2 (2003): 157-69. Web.

Kinsley, C.B., Crolla, A.M., & Higgins, J. (2002). Ammonia reduction in aerated subsurface flow constructed wetlands. In *Proceedings of the 8th International Conference on Wetland Systems for Water Pollution Control* (pp. 961-971). Dar se Salaam, Tanzania: Comprint International Limited, University of Dar Es Salaam.

Korkusuz, E. Asuman, Meryem Beklioğlu, and Göksel N. Demirer. "Comparison of the Treatment Performances of Blast Furnace Slag-based and Gravel-based Vertical Flow Wetlands Operated Identically for Domestic Wastewater Treatment in Turkey."*Ecological Engineering* 24.3 (2005): 185-98. Web. 4 Jan. 2012.

Lin, Ying-Feng, Shuh-Ren Jing, Der-Yuan Lee, and Tze-Wen Wang. "Nutrient Removal from Aquaculture Wastewater Using a Constructed Wetlands System." *Aquaculture*209.1-4 (2002): 169-84. *ScienceDirect*. June-July 2002. Web. 4 Jan. 2012.

Mæhlum, T. "Cold-climate Constructed Wetlands." *Water Science and Technology* 32.3 (1995): 95-101. Web.

Mander, U., and P. D. Jenssen. "Chapter 2: Subsurface Treatment Wetlands in the Cold Climate of Minnesota." *Constructed Wetlands for Wastewater Treatment in Cold Climates*. Southampton, UK: Boston, 2003. 19-52. Print.

Mendenhall, William, and Terry Sincich. *Statistics for Engineering and the Sciences*. 5th ed. Englewood Cliffs, NJ: Prentice-Hall, 2007. Print.

Metcalf and Eddy Inc. (1991) Wastewater Engineering, Treatment, Disposal, and Reuse. Tchobanoglous G., Burton F.L. (eds.) Third Edition, McGraw-Hill: New York.

Nivala, J., M.b. Hoos, C. Cross, S. Wallace, and G. Parkin. "Treatment of Landfill Leachate Using an Aerated, Horizontal Subsurface-flow Constructed Wetland." *Science of The Total Environment* 380.1-3 (2007): 19-27. Print.

USDA, *Natural Resources Conservation Service*. "Plants Database." 17 Jan. 2012. Web. 2012. <http://plants.usda.gov/java/charProfile?symbol=SCAT2>.

Tanner, C.C. "Plants as Ecosystem Engineers in Subsurface-flow Treatment Wetlands." *Water Science and Technology* 12th ser. 44.11 (2001): 9-17. Print.

Tanner, C., J. Sukias, and M. Upsdell. "Substratum Phosphorus Accumulation during Maturation of Gravel-bed Constructed Wetlands." *Water Science and Technology*40.3 (1999): 147-54. Web. 4 Jan. 2012.

Tchobanoglous, George, Franklin L. Burton, and H. David. Stensel. *Wastewater Engineering: Treatment and Reuse*. New York: McGraw-Hill, 2004. Print.

Thomas, P. "An Evaluation of Pollutant Removal from Secondary Treated Sewage Effluent Using a Constructed Wetland System." *Water Science and Technology* 32.3 (1995): 87-93. Web.

Vymazal, Jan. "The Use of Sub-surface Constructed Wetlands for Wastewater Treatment in the Czech Republic: 10 Years Experience." *Ecological Engineering* 18.5 (2002): 633-46. Web.

Vymazal, J. (2007). “Removal of nutrients in various types of constructed wetlands.” *Science of the Total Environment*. 380: 48-65.

Wallace, Scott D., and Robert L. Knight. *Small-scale Constructed Wetland Treatment Systems: Feasibility, Design Criteria, and O&M Requirements*. Alexandria, VA: WERF, 2006. Print.

Wallace, Scott, Jaime Nivala, and Troy Meyers. "Chapter 15: Statistical Analysis of Treatment Performance in Aerated and Nonaerated Subsurface Flow Constructed

Wetlands."*Wastewater Treatment, Plant Dynamics and Management in Constructed and Natural Wetlands*. By Jan Vymazal. Dordrecht: Springer, 2008. 171-80. Print.

Wittgren H.B., Mæhlum T. (1997) Wastewater treatment wetlands in cold climates. Water Science and Technology 35(5): 45–53.

Yang, Y. "Removal Efficiency of the Constructed Wetland Wastewater Treatment System at Bainikeng, Shenzhen." *Water Science and Technology* 32.3 (1995): 31-40. Web.