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Modeling Nitrogen Transformations in a Pilot Scale Marine Integrated Aquaculture System

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Modeling Nitrogen Transformations in a Pilot Scale Marine Integrated Aquaculture System

by

Brian McCarthy

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

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Keywords: Constructed Wetland, Geotube, Moving Bed Biofilm Reactor, STELLA™,
Recirculating Aquaculture System

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DEDICATION

I would like to dedicate this work to my family; dad, mom, Taylor, Scott and Andy.

ACKNOWLEDGMENTS

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ABSTRACT

Integrated aquaculture systems (IAS) are a type of recirculating aquaculture systems (RAS) where the wastewater is treated and returned to the fish tanks. The important difference between the two is that in an IAS, wastes from the aquaculture component are recovered as fertilizer to produce an agricultural product whereas in an RAS, waste organics, nutrients and solids are treated and discharged. A pilot marine IAS at Mote Aquaculture Research Park in Sarasota, FL was studied for this project. Water quality monitoring, measurements of fish health and growth rates of fish and plants were performed over a two-year period to determine the effectiveness of the system in producing fish and plant products and removing pollutants. The goal of this portion of the project was to develop, calibrate and evaluate a model of the system, to understand the nitrogen transformations within the Mote IAS and to investigate other potential configurations of the Mote IAS.

The model was divided into the various compartments to simulate each stage of the system, which included fish tanks, a drum filter for solids removal, and moving bed bioreactor (MBBR) for nitrification and disinfection. A solids tank after the drum filter was used to store the drum filter effluent slurry, which was then divided between three treatment processes: a geotube, a sand filter followed by a plant bed, and a plant bed alone. Nitrogen species modeled were particulate organic nitrogen (PON), dissolved organic nitrogen (DON), ammonium and nitrate. Of the physical components of the IAS, models of the MBBR and the two plant

raceways included physical, chemical and biological nitrogen transformation processes. The sand filter, solids tank and geotube models were simple mass balances, incorporating fractional removals of each species based on the observed data. Other variables modeled included temperature, dissolved oxygen, volatile suspended solids and chemical oxygen demand concentrations. The model was built in a computer program, STELLA™, to simulate the Mote IAS.

The model calibration involved experimental, literature and calibrated parameters. Parameters were adjusted until the model's output was a best fit to the observed data by minimizing the sum of the squared residuals. During the sensitivity analysis, two model parameters caused large variations in the model output. The denitrifier constant caused the most variation to the model's output followed by the denitrifier fraction of volatile suspended solids.

Of the removal processes, denitrification was the largest nitrogen removal mechanism from the model, accounting for 59% and 55% of the nitrogen removed from the south and north plant raceways respectively. Plant and soil uptake represented only 0.2% of the overall nitrogen removal processes followed by 0.1% by sedimentation.

Finally, the model was used to investigate other treatment designs if the Mote IAS was redesigned. The first option involved a geotube and one plant raceway in series to treat the solid waste while the second option did not have a geotube, but two plant raceways. The first option was the most effective at removing nitrogen while the second was as effective as the original system and would cost less.

CHAPTER 1: INTRODUCTION

Aquaculture, the farming of aquatic organisms, can minimize the need from wild caught food sources for an expanding global population (FAO, 2012). As fish consumption increases and wild caught fisheries decline, aquaculture production has increased (Figure 1-1). Aquaculture is likely to continue to play a vital role in the global food supply in the future (FAO, 2012).

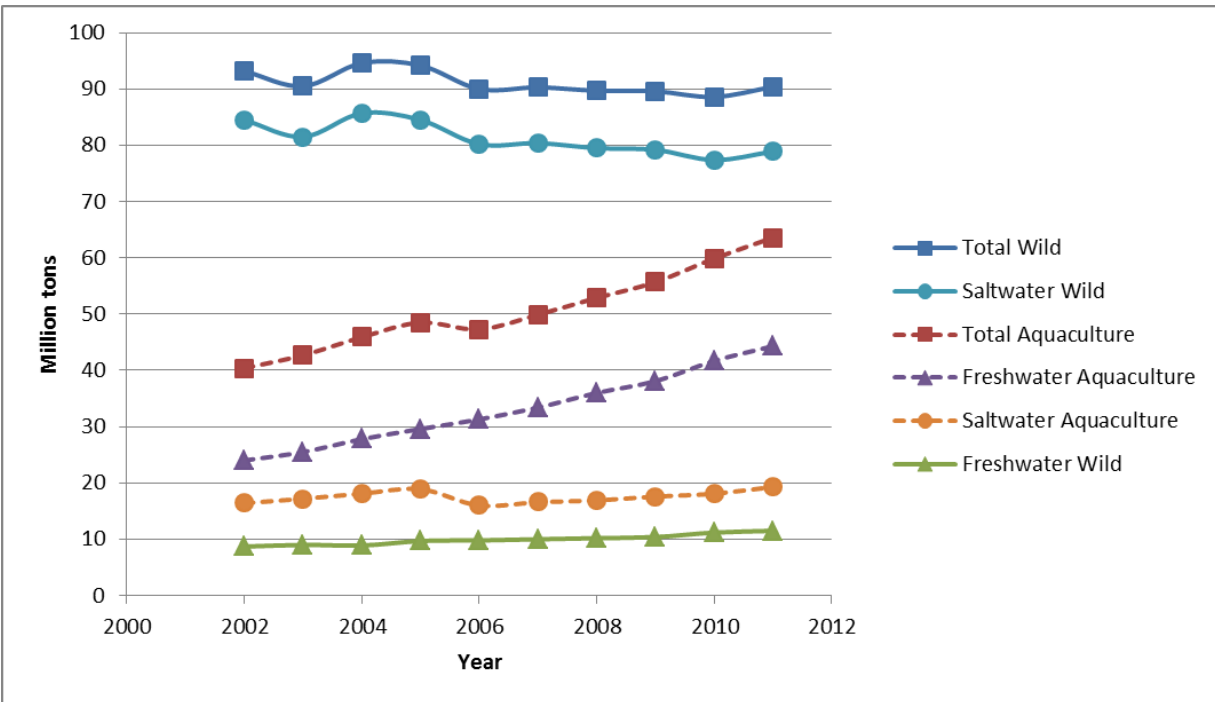


Figure 1-1. Comparison of global wild caught and aquaculture food fish production. Data taken from FAO (2008, 2012).

However, aquaculture faces a number of environmental problems. Almost all aquaculture systems produce waste nutrients, solids and organic matter and these wastes are either discharged into the environment or treated on site (Tucker et al, 2008). Nitrogen tends to be the limiting nutrient in marine environments, resulting in increased eutrophication or excess algae and plant growth. Approximately, 67% to 75% of the nitrogen in feed is lost as either uneaten feed or fish excretion (Chen and Fornshell, 2000). In raceway or pen cage aquaculture, the nitrogen load to the environment can cause eutrophication (Treece, 2000). Another potential waste damage to the environment is the release of pathogens. Since fish are produced in high densities, fish can be stressed to a point where they are vulnerable to diseases (Tucker et al., 2008). These disease causing microorganisms can be discharged into the environment; thereby effecting the local ecosystem. Additionally, the potential for the fish to escape can also effect the local ecosystem. Depending upon the system, the escaped fish can compete for resources with the endemic species, consume the endemic species if the escaped fish are predators, or can reproduce faster than the endemic species and alter the food web (Tucker et al., 2008).

A potential solution to aquaculture problems is the use of recirculating aquaculture systems (RAS). In RAS, wastewater from the fish tank is treated and recirculated back to the fish tank (Tucker et al., 2008). Some of the benefits of RAS include reduced daily water demands and greater control over fish growth and waste treatment. However, a high value market product is required to offset the high cost of water pumping and wastewater treatment in RAS.

An integrated aquaculture system (IAS) is a type of RAS that incorporates an agriculture component. In IAS, the aquaculture waste becomes a fertilizer resource for agriculture (Jamu and Piedrahita, 2002a). IAS is a low technology system, which diversifies production, promotes

efficiency and reduces discharges to the environment (FAO, 2001). From an economic standpoint, the diversification of products results in marketing flexibility. With IAS, two markets are accessible, increasing the resiliency of the production system. With respect to efficiency, the waste from one system becomes a resource for another. Finally, since nutrients are recycled from one system to the other, water and pollutant discharges to the environment are reduced (FAO, 2001).

This thesis investigates an IAS at Mote Aquaculture Research Park (MAP) in Sarasota, FL where the Florida pompano (*Trachinotus carolinus*) was the aquaculture product and red mangrove (*Rhizophora mangle*), smooth cordgrass (*Spartina alterniflora*), and black needlerush (*Juncus roemerianus*) were the agricultural products. Pompano are a resilient fish, capable of tolerating varying salinities, surviving with concentrations of dissolved oxygen (DO) as low as 3.0 mg/L and high turbidities (Craig, 2000). In Florida, pompano fisheries are in decline because it is an important species in sport and commercial activities (Murphy et al., 2008). In 2009, whole pompano cost \$6.93/kg, while pompano fillets ranged from \$35/kg to \$45/kg (Weirich, 2011). Growing pompano in IAS will result in the production of a high value fish and offset costs associated with IAS.

Selection of salt tolerant plants for IAS that are in demand can be challenging. In Florida, one of the most important salt tolerant plants along the coast is the mangrove (Florida DEP, 2012). Mangroves trap various organic and chemical nutrients with their elongated root structure and help filter the water. Their root system also acts as a nursery for many species of fish, which have a significant recreational value. Mangroves, however, have been removed to make way for development in the Southeastern United States. Depending upon the location, developers who want to remove mangroves have the opportunity to mitigate this activity through

a wetland mitigation program. Wetland mitigation provides a market for the sale of mangroves. Aquatic Plants of Florida sells three gallon red mangrove plants at \$12.50 per plant, providing a second revenue stream for the IAS (Aquatic Plants of Florida, 2012).

It is important to model an IAS, such as the one at MAP, so private companies can design full scale systems. By supplying feed input rates and composition, a model can be used to size efficient water treatment systems and plant beds. Feed input rates can be estimated based on the fish growth rates and feed conversion efficiency. Providing private companies a model for design also allows them to increase employment. There are an estimated four jobs produced for every one job in fisheries and aquaculture production in auxiliary industries, such as fish processing equipment, ice production, or packaging (FAO, 2008). Another important reason to model IAS is to understand nutrient removal mechanisms. Few prior modeling studies have been done on IAS. Jamu and Piedrahita (2002a) built an IAS model based on pond aquaculture. Their model included nutrient cycling between aquaculture and agriculture, but also included an effluent discharge from the pond after harvesting. The Mote IAS model was built without an effluent discharge to simulate a zero discharge RAS.

Seven fish tanks were available for fish production in the Mote IAS. The waste stream from the fish tanks were sent to a drum filter where the solids and liquids were separated (Figure 1-2). The liquid waste stream was treated by a moving bed biofilm reactor (MBBR) and a UV disinfection unit. The solid waste stream was divided into two plant raceway systems and a geotextile bag, or geotube. The effluent from the plant raceways and geotube was recirculated back to the drum filter. This project was funded by the National Oceanic and Atmospheric Administration for a two year period, beginning October 2010. Two students at the University of South Florida investigated water quality (Kruglick, 2012) as well as soil and plant analysis

(Boxman, 2013). This thesis is a continuation of the project by using the data collected by Kruglick (2012) and Boxman (2013) and developing a model to investigate the mechanisms of nitrogen removal in the Mote IAS.

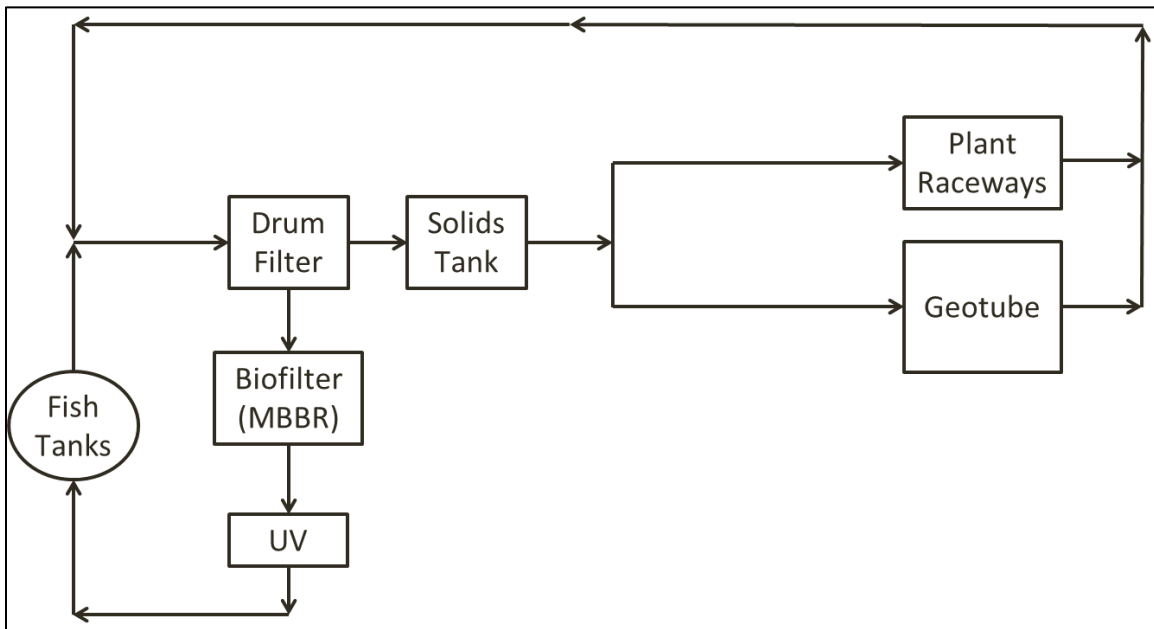


Figure 1-2. Diagram of Mote IAS.

The overall goal of this research was to understand the nitrogen removal and transformation processes in a marine IAS for future IAS development. The three objectives were:

1. Develop, calibrate and evaluate a marine IAS model used to simulate the fate of nitrogen in the Mote IAS.
2. Understand the fate of nitrogen in a marine IAS.
3. Apply this model to evaluate two Mote IAS reconfiguration scenarios.

CHAPTER 2: LITERATURE REVIEW

There are a limited number of journal articles pertaining to marine IAS. Thus, it was important to subdivide the literature review into specific parts pertaining to each aspect of marine IAS. An overview of the nitrogen cycle is presented, followed by modeling of RAS, modeling of IAS, and finishing with modeling of constructed wetlands.

2.1 Nitrogen Cycle

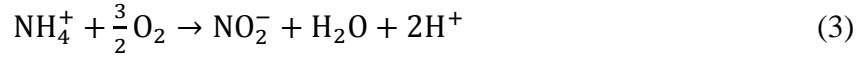
Representing 78% of the atmosphere, nitrogen gas ($N_{2(g)}$) is bioavailable only to a few groups of microorganisms that have the ability to fix atmospheric nitrogen (Vaccari et al, 2006). Nitrogen fixation can occur near the root zone of plants or in the sediment and under aerobic or anaerobic conditions (US EPA, 2000). Other nitrogen fixation processes include lightning and industrial practices that can fix nitrogen gas into NH_4^+ and NO_3^- for fertilizer production (US EPA, 1993). One general form of nitrogen fixation is given by:



Ammonification is the process in which organic nitrogen compounds (RNH_2), such as those in plant and animal waste, are converted to NH_4^+ (Schlesinger, 1997). Ammonification can occur under aerobic and anaerobic conditions (NRCS, 2007). Ammonification is also temperature dependent; as temperature increases, ammonification increases (US EPA, 2000). Depending upon the organic compound, ammonification can proceed as follows:

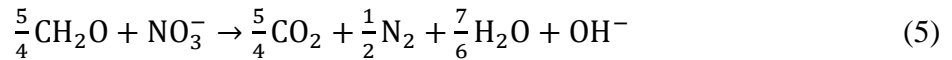


Nitrification is a two-step process where NH_4^+ is converted to NO_3^- (US EPA, 1993) and is given by:



In the first step (Equation 3), bacteria such as *Nitrosomonas* oxidize ammonium to nitrite. In the second step (Equation 4), bacteria such as *Nitrobacter* rapidly oxidize nitrite to nitrate. Nitrification occurs under aerobic conditions and is temperature and pH dependent (US EPA, 2000).

Finally, nitrogen is returned to the atmosphere through denitrification to complete the nitrogen cycle. Denitrification occurs under anoxic conditions and is represented by:



If NH_4^+ and NO_3^- are available in soil, plants can uptake the nitrogen and convert it into biomass. Through plant decay, the organic nitrogen is returned to the soil where ammonification can reoccur (US EPA, 1993). The plant uptake of nitrogen creates a mini nitrogen cycle where the nitrogen is not required to return to the atmosphere.

A conceptual model of the nitrogen cycle in the Mote IAS is shown in Figure 2-1. The plant beds in the Mote IAS are similar to constructed wetlands. In a constructed wetland, plants can be considered as a source of organic nitrogen as the biomass decays. However, if plants are harvested at a young age, plant decay may not be considered. Particulate organic nitrogen (PON) has three different pathways in a constructed wetland. First, PON can proceed to dissolved organic nitrogen (DON) via hydrolysis. Hydrolysis is the process where large particles are physically and chemically broken down into smaller particles that can be utilized by

microorganisms (Rittman and McCarty, 2001). Second, PON can accumulate in the plant soil and be removed from the system at plant harvest. Lastly, PON can settle underneath the plant containers via sedimentation and remain there until physically removed from the system. Similar to the general nitrogen cycle, ammonification (Equation 2) converts DON to NH_4^+ .

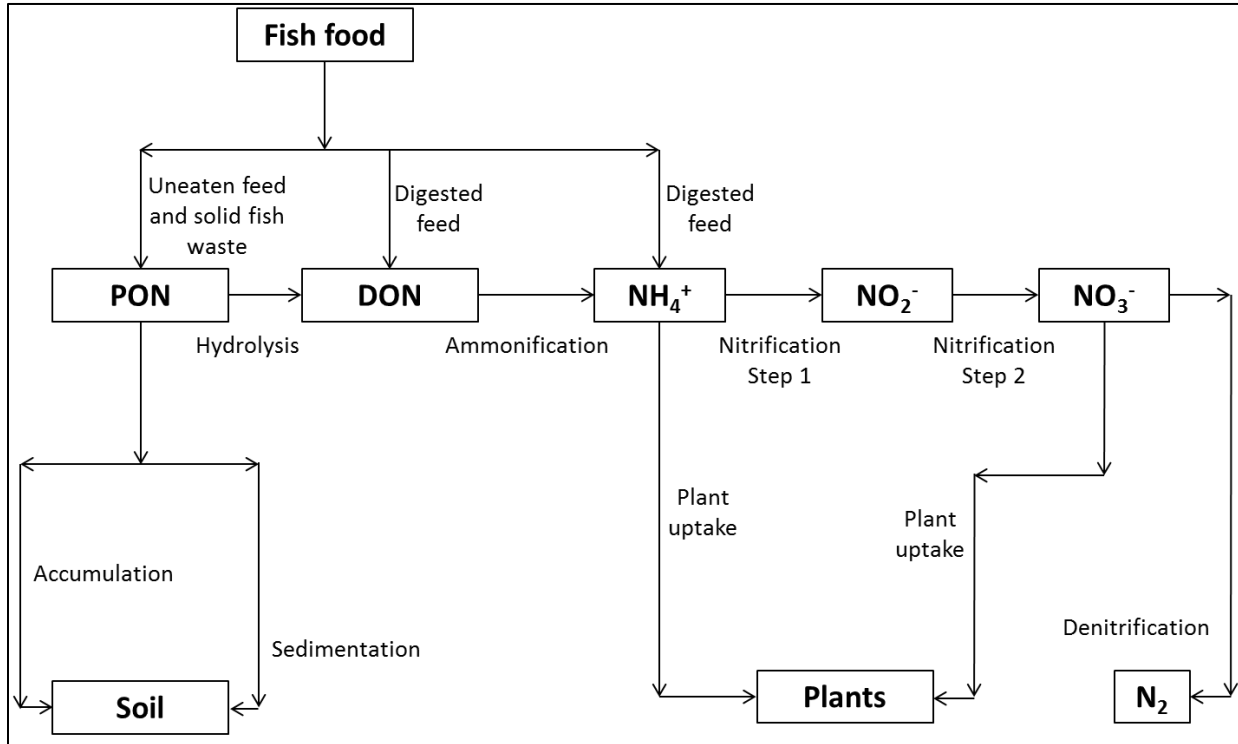


Figure 2-1. Conceptual model of the nitrogen cycle in an IAS.

NH_4^+ and NO_3^- also follow similar pathways in IAS as in the general nitrogen cycle. In the IAS, NH_4^+ is converted to NO_3^- via nitrification (Equations 3 and 4), mainly in the biofilter. Biofilters used in RAS or IAS include trickling filters, rotating biological contactors (RBC) or MBBRs. All three biofilters are attached growth systems where a biofilm will grow on a media, composed of plastic, sand or rock material (Vaccari et al., 2006). In a trickling filter, the media does not move as the wastewater trickles through the media. In a RBC, large disks with attached

biofilm rotate through the wastewater. In a MBBR, the plastic media is suspended in a basin with the wastewater. NH_4^+ can also be removed by plant uptake. Finally, denitrification removes nitrate by releasing nitrogen gas into the atmosphere (Equation 5).

2.2 RAS Models

Losordo and Hobbs (2000) presented a RAS model that used computer based spreadsheets to estimate the required biofilter size needed to maintain the desired water quality. This model can be used by someone with little modeling experience and focused on five separate areas: the fish tank size and biomass, total ammonia nitrogen (TAN) mass balance, biofilter sizing, solids mass balance and oxygen mass balance. The model was based on a previous study utilizing a trickling filter and drum screen filter while growing tilapia. The user inputs various system parameters and goals for their system. With respect to nitrogen, inputs include the following: feed protein content, desired TAN concentration, passive nitrification and denitrification rates, maximum NO_3^- concentration as well as TAN removal efficiency of the biofilter. There was no denitrification component to this model; however the model calculates the amount of water required to be added per day in order to maintain the maximum NO_3^- concentration. With this information, the model estimates the flow rate required to maintain the target TAN concentration and the amount of water that needs to be replaced to maintain the maximum NO_3^- concentration for the RAS. This model does not simulate the details of the nitrogen cycle within a RAS but could be used for “back of the envelope” calculations for RAS construction.

Wik et al. (2009) investigated nitrogen transformations using a RAS model with multiple MBBRs. This model was built for Matlab and each component was based on transient states

(non-steady state). The model was separated into three parts: fish model, waste production and waste treatment. Within the fish model, the subcomponents included growth and feeding. After feeding, waste production increases to a point before decreasing, as the model takes into account the digestion of the fish, where there was a residence time from the time feed was consumed to when it was digested and released into the environment.

In the second model component, waste production was divided into four categories: feed not consumed by fish, consumed and digested, consumed and absorbed and finally consumed and respired. Each of the four categories contains various amounts of organic or inert material, various nitrogen constituents, phosphorus and dissolved carbon dioxide. This allows the model to calculate loading rates of different constituents to the MBBRs.

Within the last component, the MBBRs were modeled using the activated sludge model number 1 (ASM 1) but modified for MBBRs used in aquaculture. The MBBRs were modeled as biofilm reactors in series with both suspended sludge and biofilm media. The first was a denitrification MBBR, followed by an aerobic MBBR for BOD removal, a sand filter to collect sludge and ending with a nitrification MBBR.

Their work provides a framework for modeling RAS. From their simulations, they concluded the following:

- the entire system should be modeled as a dynamic system,
- organic carbon was the limiting factor in denitrification and the addition of organic carbon can cause concentration oscillations due to the recirculation,
- building a “by-pass” over the nitrification MBBR can improve performance and reduce the required reactor volumes.

Wik et al. (2009) described sixteen different waste products from aquaculture. The nitrogen waste products include five forms: DON, PON, NO_3^- , nitrite and NH_4^+ . One drawback to this model was that the case study used was a theoretical example. The model was not calibrated or validated with a real world case. Another drawback was the use of ASM 1, which is an activated sludge model, for an attached growth reactor. Current models, such as BIOWIN and GPXS, are now available for biofilm reactors.

2.3 IAS Models

Jamu and Piedrahita (2002a and 2002b) developed an IAS model to simulate the dynamics of organic matter and nitrogen through aquaculture and agriculture. Previous aquaculture models lacked the dynamic aspect and excluded important biological, physical or chemical processes to accurately predict the water quality.

The IAS model was divided into two components: aquaculture and agriculture. The model built upon existing models, such as a pond ecosystem model (Nath, 1996; Piedrahita, 1990) and a basic crop model (Spitters et al., 1989), but was different from previous models by its treatment of nitrogen, organic matter and soil sediments. Nitrogen was considered a major dynamic component because nitrogen was required for plant growth yet some forms are detrimental to fish populations. Furthermore, organic matter plays an important role in recycling nutrients in the ecosystem. Finally, the sediments play a role in nitrogen transformation processes and plant growth.

The aquaculture and agriculture components can be modeled separately or integrated as one system, connected by a cycle. After the initial harvest of plants, the crop waste was used to fertilize the aquaculture pond. During fish growth, the pond water was used to irrigate the crops.

After fish were harvested, the aquaculture pond sediments were used as the initial sediments for the crop.

Only the aquaculture model was calibrated because the agriculture model was validated using data from a previous study (Spitters et al., 1989). Each aquaculture sub-model was calibrated until a general fit was achieved. The data used to calibrate the model was from a site in Rwanda where the crop waste was used as a pond fertilizer (Berkman, 1995).

Model verification was performed by comparing the output of the model to data from sites in Honduras, Thailand and Malawi (Berkman, 1995). Since each site had different site specific details, the model was recalibrated for each site. The model was evaluated and deemed satisfactory as simulations were within one standard deviation of the observed data. The sensitivity analysis was performed by varying different rate coefficients. To determine which ones were the most sensitive, the rate coefficients were ranked based upon the magnitude of their values. Lastly, the verification step showed that their model fit within two of the three sites, with Thailand not fitting into the model. The zooplankton and phytoplankton may account for this discrepancy because the fish may have had different grazing preferences.

A model developed by Jamu and Piedrahita (2002a and 2002b) provided a good reference for the Mote IAS model but required some adjustments. Feed in the Jamu and Piedrahita model included phytoplankton that grew within the fish pond. If the phytoplankton component did not produce enough feed for the fish, a fertilizer feed was added. Within the Mote IAS, the Florida pompano do not consume phytoplankton. Thus the commercial feed was the only outside input of nitrogen to the system. Another difference is that Jamu and Piedrahita (2002a) simulated the diffusion of nitrogen species using a sediment column model and allowed for losses of nitrogen into the upper and lower layers of the sediment. Since the Mote IAS has a liner, a sediment

column component was not included. One last major difference is the Jamu and Piedrahita model was a freshwater system. A salinity factor needed to be included in the Mote IAS.

2.4 Constructed Wetland Models

Kadlec and Wallace (2009) describe a simple nitrogen model for constructed wetlands (Figure 2-2). Some of the influent organic nitrogen is converted to NH_4^+ via ammonification. Wastewater treatment literature often combines organic nitrogen and NH_4^+ as total Kjeldahl nitrogen, assuming that ammonification is instantaneous (Kadlec and Wallace, 2009). However, Kadlec and Wallace (2009) explain that ammonification is not instantaneous in constructed wetlands because of the background concentrations of organic nitrogen from plant residuals. Another simplifying assumption Kadlec and Wallace (2009) made in the model was that plants only use NH_4^+ for growth.

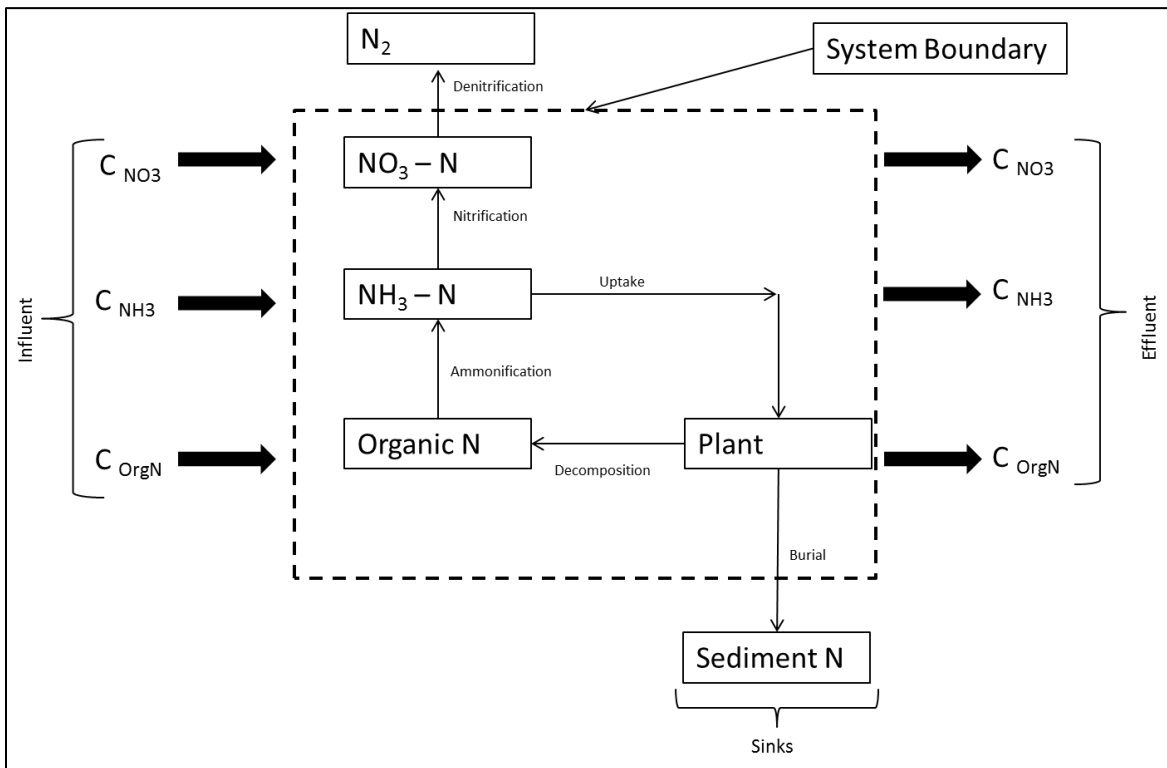


Figure 2-2. Simplified constructed wetland model (adapted from Kadlec and Wallace, 2009).

Mayo and Mutamba (2005) developed a model to investigate nitrogen removal from a university's wastewater by treating it with a high rate pond (HRP) followed by an unplanted horizontal subsurface flow constructed wetland. A pilot system was constructed to collect data for the model, including pH, DO, NO_3^- , nitrite, NH_3 and chemical oxygen demand (COD) concentrations. A mass balance was performed for organic nitrogen, NH_3 and NO_3^- within the HRP and the constructed wetland. A conceptual model of the constructed wetland component is shown in Figure 2-3.

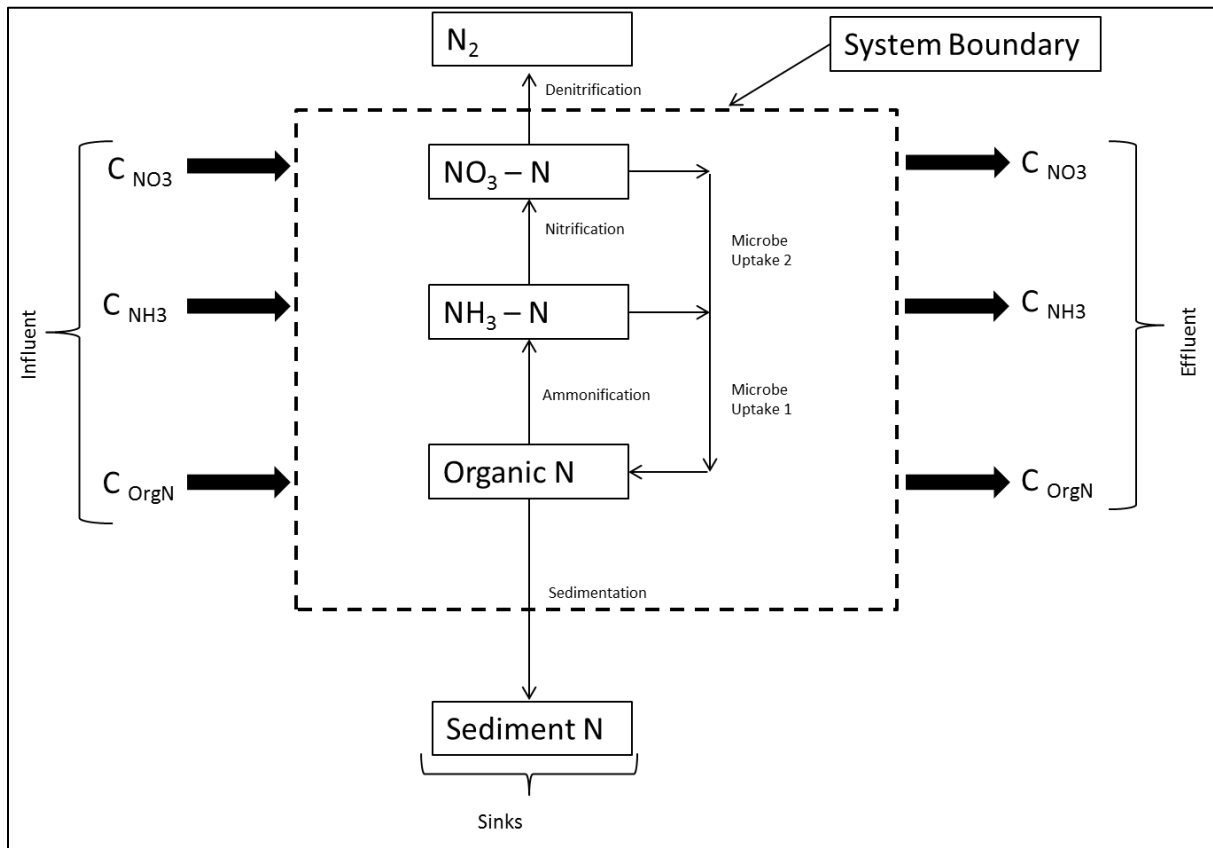


Figure 2-3. Constructed wetland component of model (adapted from Mayo and Mutamba, 2005).

This model assumed that as microorganisms utilize NH_3 and NO_3^- , the waste and decay products became organic nitrogen. These organisms included suspended and attached bacteria. Ammonification was modeled using an equation developed by DiToro et al (1971), where the water temperature influences the reaction rate. For the amount of organic nitrogen loss to the sediments, the model followed Stokes Law for small particles. The nitrification process was modeled using Monod kinetics, with terms that considered temperature, DO and pH. Unlike other wastewater models, the Mayo and Mutamba (2005) model used an exponential equation for temperature, developed by Downing (1996). Below a pH value of 7.2 and above 9.3, *Nitrosomonas* are not as effective. The model used an “if then else” function depending upon the pH to influence nitrification. The denitrification process was also modeled using Monod kinetics and the rate was a function of temperature, organic carbon and NO_3^- concentration.

Wynn and Liehr (2001) built a constructed wetland model and calibrated it with data from a constructed wetland in Maryland. The model was used to demonstrate the effect of microbial growth on the carbon and nitrogen cycles. Previous models examined by Wynn and Liehr (2001) adjusted for pH and temperature, but considered microbial growth and decay as a “black box.” This model consisted of six components that include the nitrogen, carbon and water cycles, growth of autotrophic and heterotrophic microorganisms and the DO budget.

Examining the nitrogen cycle, Wynn and Liehr (2001) decided to model ammonification, nitrification, denitrification, microbial uptake and sedimentation with respect to PON, DON, ammonium and nitrate. Plant uptake of nutrients was not considered in this constructed wetland model. Instead, plant growth was assumed to occur at a constant rate if water and nutrients were in abundance. Thus, plant growth only contributed as an input to the PON via plant decay once the growing season was completed.

The microorganism component for autotrophs and heterotrophs were modeled based on Monod kinetics (Wynn and Liehr, 2001). The autotrophic component represented *Nitrosomonas* with limiting reactants of ammonium and DO. The heterotrophic component represented aerobic and anaerobic microorganisms with limiting reactants of total organic carbon and DO. Both autotrophic and heterotrophic microorganisms' death rates were based on a first order reaction rate.

Table 3-1. Description of physical components of the Mote IAS.

Item	Dimensions	Volume (L)	Notes
Fish tank	Six 3m diameter tanks and one 6m diameter tank	89,000	Dolphin Fiberglass Products, Miami, FL.
Drum filter	Equipped with a 60 µm screen for solids filtration.	2,800	PR Aqua Drum Filter, Model RFM 3236, Nanaimo, BC, Canada.
Solids tank	3m diameter tank	7,100	Received the solids backwash from the drum filter.
Sand filter	2.4m x 2.4m	5,760	Two sand filters acted as solids pretreatment prior to the north plant raceway.
Plant raceways	18m x 4.5m	50,000	Two plant raceways contained Smooth Cordgrass (<i>Spartina alterniflora</i>), Black Needle Rush (<i>Juncus roemerianus</i>) and Red Mangrove (<i>Rhizophora mangle</i>).
Geotube	3m x 3m	13,500	Ten Cate Nicolon, Commerce, GA. A polymer was periodically added to help coagulate the solids.
MBBR	6m x 3m	27,000	Contained 350 m ² /m ³ KMT media (Fureneset, Norway) with a fill fraction of 60%.

3.2 Water Quality Sampling and Analysis

Water samples were collected and concentrations of COD, total suspended solids (TSS), volatile suspended solids (VSS), total nitrogen (TN), NH₄⁺, NO₃⁻, total phosphorus and orthophosphate were measured using Standard Methods (Eaton et al., 2005) and HACH tests kits, as shown in Table 3-2. TSS and phosphorus concentrations were not used in the model. Soil and plant samples were collected on three separate site visits and TN and total phosphorus concentrations were measured in the plant tissues (Boxman 2013). More detailed explanations

of the sampling processes and laboratory experiments can be found in Kruglick (2012) and Boxman (2013). Measurements were made at the Environmental Engineering laboratories at the University of South Florida (USF), Tampa, FL and at Mote Marine Laboratories in Sarasota, FL. USF samples of NH_4^+ and Mote samples of NO_3^- were used for comparison with the model results. NO_3^- samples analyzed by USF were not used because there were initial problems with NO_3^- laboratory testing. NH_4^+ samples analyzed by Mote were not used because USF had more data than Mote.

Table 3-2. Measured water quality constituents and measurement methods.

Parameter	Units	Unfiltered	Filtered	Method Detection Limit	Method*
TN	mg/L N	X	X	1.34	Hach Method 10071 (Persulfate Digestion).
NH_4^+	mg/L NH_4^+ -N		X	0.012	Hach Method 10023 (Salicylate Method).
NO_3^-	mg/L NO_3^- -N		X	0.207	Resorcinol method (Zang and Fischer, 2006).
COD	mg/L	X		3.06	Hach Method 8000, 40 CFR 136.3; SM 5220 D.
DO	mg/L			N/A	Quanta Hydrolab multimeter probe (Loveland, CO).
Temperature	$^{\circ}\text{C}$			N/A	Quanta Hydrolab multimeter probe (Loveland, CO).
VSS	mg/L	X		N/A	Standard Methods (2540 E).
*Additional methodology information can be found in Kruglick (2012) and Boxman (2013).					

3.3 Mass Balances

The Mote IAS was a closed loop system (Figure 3-1), where the water was recirculated, moving through different stages. The model was therefore broken into components that represented the different processes of the IAS. Transformations of PON, DON, NH_4^+ -N and NO_3^- -N were examined through each component (Figure 3-2). Each stage had some or all of the

various transformations occurring. For example, the solids tank, drum filter and MBBR did not have any plant uptake. For a complete list of assumptions for each physical stage, see Appendix B. Volatilization of NH_4^+ was not considered because the pH was too low.

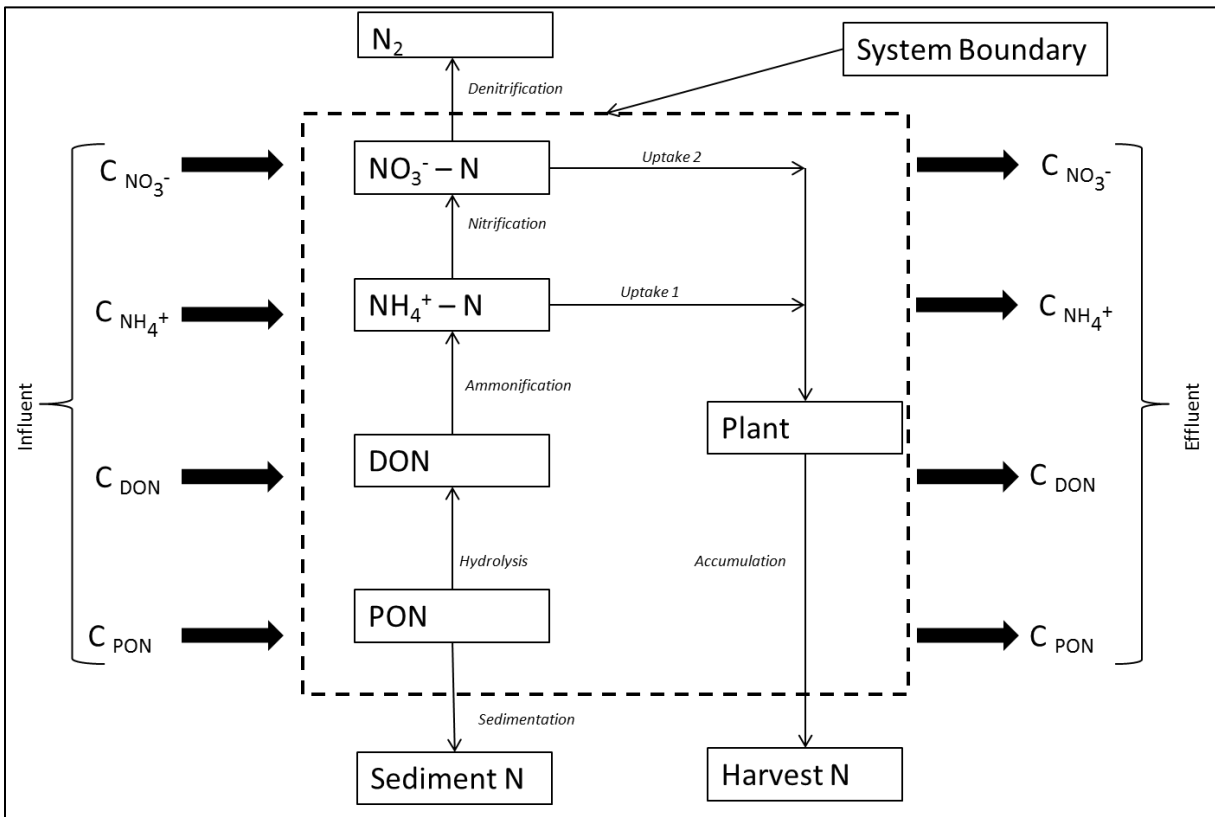


Figure 3-2. Overall conceptual model of nitrogen transformations in the IAS.

3.3.1 Fish Tank Mass Balance

Water samples were not collected from the fish tank. The equations used for the fish tank component were based upon current literature and data on feed rates. The physical dimensions of the seven fish tanks can be found in Table 3-1. The main source of nitrogen input to the IAS was by feed added to the fish tanks. As shown in Figure 3-3, feed input increased or decreased based upon the requirements of the fish. The feed was Zeigler Finfish Silver (Zeigler, N.D.) and

was comprised of a minimum of 40% crude protein, a minimum of 10% crude fat, a maximum of 4% crude fiber, a maximum of 12% moisture and a maximum of 8% ash. It was assumed that nitrogen was contained only in the crude proteins.

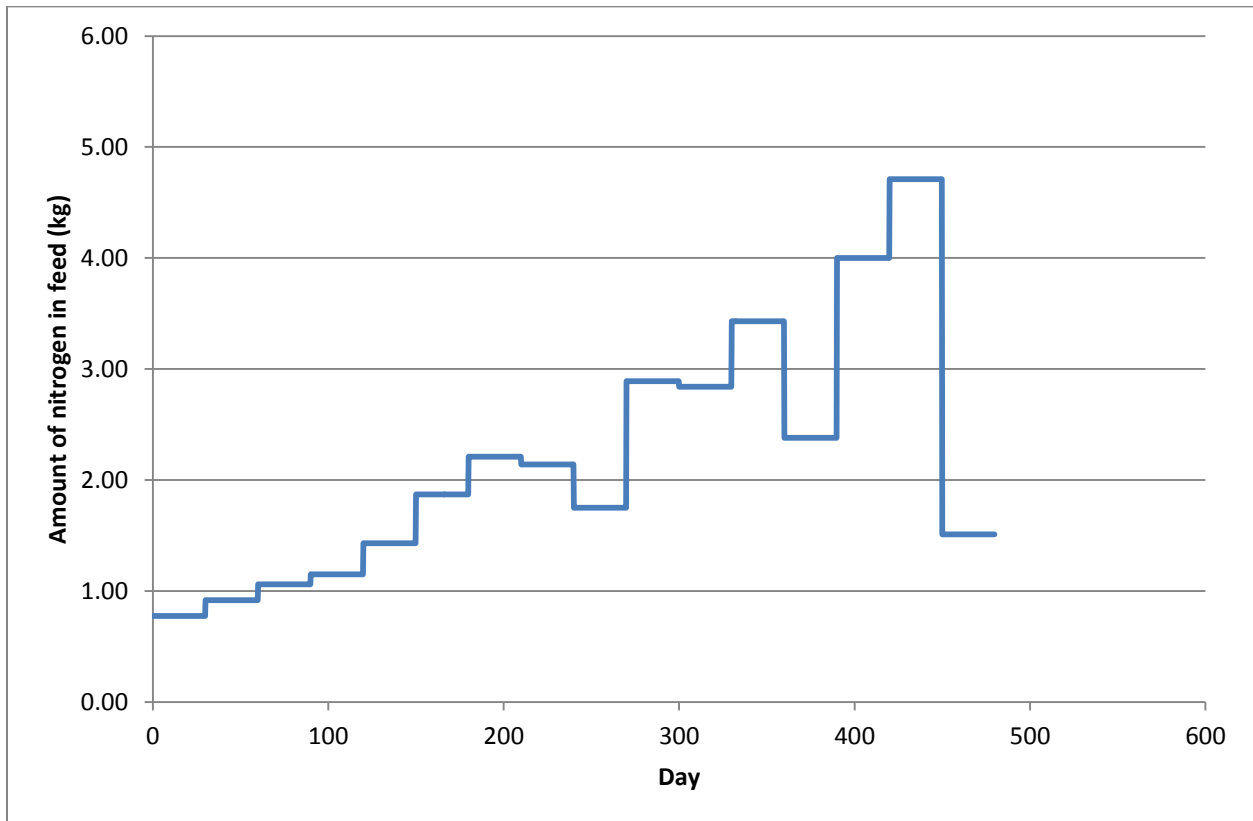


Figure 3-3. Amount of nitrogen in feed entering Mote IAS on a daily basis.

In the Mote IAS, automated feeders were attached to the fish tanks and fed continuously for 12 hours. If total daily feed was added once a day, then the concentration of nitrogen species will peak four to six hours after feeding and a constant nitrogen concentration cannot be assumed (Timmons et al., 2002). Since feed was applied continuously for 12 hours, it was assumed that the nitrogen concentration in the fish tank was constant.

The feed conversion efficiency (FCE) is a measure of how much biomass is gained per unit mass of feed applied (Ernst, 2000). Weirich et al. (2009) investigated the FCE of Florida pompano and found the FCE ranged from 25% to 46%. Thus, of the feed applied, 54% to 75% was wasted by the fish.

An overview of how the nitrogen in fish feed is divided into fish biomass, PON, DON and NH_4^+ is presented in Figure 3-4. According to Chen and Fornshell (2000), 67% - 75% of the nitrogen in fish feed will be lost as either feed waste or excretion. Therefore, approximately 25% - 33% of the nitrogen added to the system will be retained within the fish biomass. Of the nitrogen consumed and excreted, 70% - 90% is metabolized into NH_4^+ (Chen and Fornshell, 2000). For marine fish, Jobling (1994) found that the nitrogen in the fish waste can represent up to 30% - 40% of the TN in the tank. In this model, it was assumed that fish excretion consisted of only DON and NH_4^+ . Fish may also excrete PON, but it was assumed that the PON would be rapidly hydrolyzed into DON.

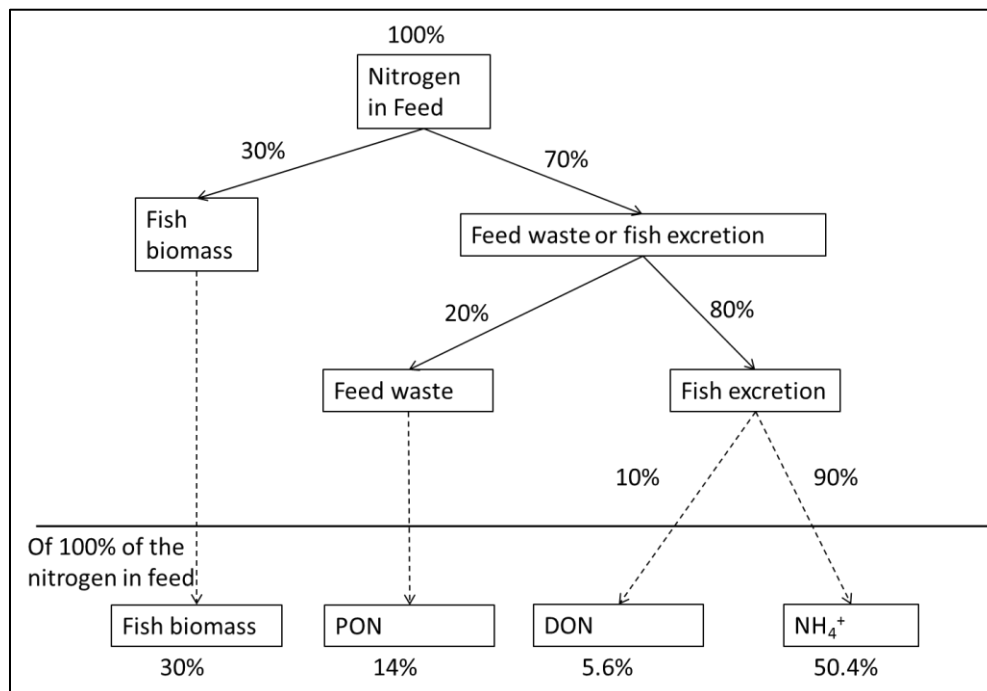


Figure 3-4. Overview of how feed was divided into different nitrogen species.

A mass balance on PON in the fish tank is given by:

$$V_{FT} \frac{dC_{8P}}{dt} = Q_7 C_{7P} + f_P r_{feed} V_{FT} - Q_7 C_{8P} \quad (6)$$

where V_{FT} is the volume of the fish tank (L), C_{8P} is the PON concentration in the fish tank (mg/L), Q_7 is the flow through the MBBR (L/day), C_{7P} is the PON concentration from the MBBR (mg/L), f_P is the fraction of feed in the fish tank converted to PON and r_{feed} is the rate of feed added to the fish tanks (mg/L*day).

A mass balance on DON in the fish tank is given by:

$$V_{FT} \frac{dC_{8D}}{dt} = Q_7 C_{7D} + f_D r_{feed} V_{FT} - Q_7 C_{8D} \quad (7)$$

where C_{8D} is the DON concentration in the fish tank (mg/L), C_{7D} is the DON concentration from the MBBR (mg/L) and f_D is the fraction of feed in the fish tank converted to DON.

A mass balance on NH_4^+ -N in the fish tank is given by:

$$V_{FT} \frac{dC_{8A}}{dt} = Q_7 C_{7A} + f_A r_{feed} V_{FT} - f_{ni} Q_7 C_{7A} - Q_7 C_{8A} \quad (8)$$

where C_{8A} is the NH_4^+ -N concentration in the fish tank (mg/L), C_{7A} is the NH_4^+ -N concentration from the MBBR (mg/L), f_A is the fraction of feed in the fish tank converted to NH_4^+ -N and f_{ni} is the fraction of NH_4^+ -N nitrified in the fish tank. Nitrification occurs in the fish tank due to aerobic conditions and the presence of nitrifying bacteria attached to the tank surfaces (Losordo and Hobbs, 2000). Little to no biofilm was observed on the walls of the fish tanks, most likely due to the shear forces caused by flow. An assumption that only 10% of the NH_4^+ -N was nitrified was made.

Since NO_3^- -N is not excreted by fish, the only source of NO_3^- -N is nitrification. A mass balance on NO_3^- -N in the fish tank is given by:

$$V_{FT} \frac{dC_{8N}}{dt} = Q_7 C_{7N} + f_{ni} Q_7 C_{7A} - Q_7 C_{8N} \quad (9)$$

where C_{8N} is the NO_3^- -N concentration in the fish tank (mg/L) and C_{7N} is the NO_3^- -N concentration from the MBBR (mg/L).

3.3.2 Drum Filter Mass Balance

Water from the fish tank, south and north plant raceways and geotube flowed to an Aqua Drum Filter (PR AquaSupplies, Nanaimo, BC, Canada). The drum filter separated the water and the solids. A rotating microscreen filters the water and captures the solids. Since there were no samples collected prior to the drum filter, a simple mass balance was used to determine the drum filter influent assuming no transformations or losses of nitrogen species:

$$Q_7C_{8P} + Q_2C_{2P} + Q_2C_{3P} + Q_2C_{4P} = Q_9C_{9P} \quad (10)$$

$$Q_7C_{8D} + Q_2C_{2D} + Q_2C_{3D} + Q_2C_{4D} = Q_9C_{9D} \quad (11)$$

$$Q_7C_{8A} + Q_2C_{2A} + Q_2C_{3A} + Q_2C_{4A} = Q_9C_{9A} \quad (12)$$

$$Q_7C_{8N} + Q_2C_{2N} + Q_2C_{3N} + Q_2C_{4N} = Q_9C_{9N} \quad (13)$$

where Q_2 is the flow of the south or north plant raceway or geotube (L/day), C_{2P} , C_{3P} , C_{4P} and C_{9P} are the PON concentrations of the south plant raceway, north plant raceway, geotube and drum filter, respectively (mg/L), Q_9 is the flow through the drum filter (L/day), C_{2D} , C_{3D} , C_{4D} and C_{9D} are the DON concentrations of the south plant raceway, north plant raceway, geotube and drum filter, respectively (mg/L), C_{2A} , C_{3A} , C_{4A} and C_{9A} are the NH_4^+ -N concentrations of the south plant raceway, north plant raceway, geotube and drum filter respectively (mg/L) and C_{2N} , C_{3N} , C_{4N} and C_{9N} was the NO_3^- -N concentration of the south plant raceway, north plant raceway, geotube and drum filter, respectively (mg/L).

The drum filter was assumed to only transport nitrogen, not transform it. Using laboratory data from Kruglick (2012) and Boxman (2013), an estimated average of the drum

filter effluent for each nitrogen species going to the MBBR and solids tank was calculated. A mass balance on the drum filter effluent is given by:

$$Q_9 C_{9P} = Q_7 C_{6P} + Q_1 C_{10P} \quad (14)$$

$$Q_9 C_{9D} = Q_7 C_{6D} + Q_1 C_{10D} \quad (15)$$

$$Q_9 C_{9A} = Q_7 C_{6A} + Q_1 C_{10A} \quad (16)$$

$$Q_9 C_{9N} = Q_7 C_{6N} + Q_1 C_{10N} \quad (17)$$

where Q_1 is the flow through the solids tank (L/day), C_{6P} and C_{10P} are the PON concentrations entering the MBBR and solids tank (mg/L), respectively, C_{6D} and C_{10D} are the DON concentrations entering the MBBR and solids tank (mg/L), respectively, C_{6A} and C_{10A} are the NH_4^+ -N concentrations entering the MBBR and solids tank (mg/L), respectively, and C_{6N} and C_{10N} are the NO_3^- -N concentrations entering the MBBR and solids tank (mg/L), respectively.

3.3.3 Solids Tank Mass Balance

As the water flow in the drum filter slowed, the solids were removed from the microscreen by backwashing. The solids slurry backwashed from the microscreen flowed to a solids tank. The solids tank retained the effluent after each backwash cycle until a float switch was activated. Once the float switch activated, the solids tank would flush out the backwash effluent into three different flow pathways: south and north plant raceways and the geotube. It was assumed that the flow was equally divided between the three flow pathways. Since no solids tank influent data was collected, the only assumed processes occurring in the solids tank was ammonification and denitrification. Ammonification was assumed to take place because of the high observed NH_4^+ -N concentrations observed in the solids tank effluent. Denitrification was assumed to take place because the observed averaged DO concentration was 1.2 mg/L in the

solids tank (Boxman, 2013). PON, DON, NH_4^+ -N and NO_3^- -N mass balances in the solids tank are given by:

$$V_{ST} \frac{dC_{1P}}{dt} = Q_1 C_{10P} - Q_1 C_{1P} \quad (18)$$

$$V_{ST} \frac{dC_{1D}}{dt} = Q_1 C_{10D} - r_{mi} V_{ST} - Q_1 C_{1D} \quad (19)$$

$$V_{ST} \frac{dC_{1A}}{dt} = Q_1 C_{10A} + r_{mi} V_{ST} - Q_1 C_{1A} \quad (20)$$

$$V_{ST} \frac{dC_{1N}}{dt} = Q_1 C_{10N} - f_{de} Q_1 C_{1N} - Q_1 C_{1N} \quad (21)$$

where V_{ST} is the volume of the solids tank (L), C_{1P} is the PON concentration in the solids tank (mg/L), C_{1D} is the DON concentration in the solids tank (mg/L), r_{mi} is the rate of mineralization (mg/L*day), C_{1A} is the NH_4^+ -N concentration in the solids tank (mg/L), C_{1N} was the NO_3^- -N concentration in the solids tank (mg/L) and f_{de} is the fraction of NO_3^- -N that was denitrified in the solids tank. Due to the low DO concentration, it was assumed that the nitrate in the solids tank was reduced by 15% via denitrification.

Mineralization is a process where an organic compound is transformed into an inorganic one (Senzia et al., 2002). With respect to nitrogen, ammonification transforms organic nitrogen into inorganic nitrogen or DON into NH_4^+ -N. The rate of ammonification was dependent upon the water temperature and is given by:

$$r_{mi} = k_{mi} C_{1D} \quad (22)$$

$$k_{mi} = 0.002 * T \quad (23)$$

where k_{mi} is a rate constant for ammonification (1/day) and T is the water temperature ($^{\circ}\text{C}$). Senzia et al. (2002), Mayo and Mutamba (2005) and Jamu and Piedrahita (2002) used this equation to model ammonification, which was developed by Di Toro et al. (1971).

Temperature was modeled using a simple sine wave equation. The hottest and coldest days represented the peaks of the temperature graph. Equation 24 was used to model the water temperature in the plant raceway.

$$T = T_A * \sin\left(D \frac{2\pi}{T_P}\right) + T_0 \quad (24)$$

where T_A is the amplitude of the sine wave ($^{\circ}\text{C}$), D is the day (day), T_P is the period of the sine wave (day) and T_0 is the average water temperature of the plant raceway ($^{\circ}\text{C}$). The coldest observed water temperature was 15.4°C and the hottest was 31.3°C (Boxman, 2013) over the course of a year. The average temperature of the plant raceways (T_0) was 23.35°C , with amplitude (T_A) of 7.95°C over a period (T_P) of 365 days.

3.3.4 MBBR Mass Balance

An MBBR has characteristics of both suspended growth and biofilm reactors (Odegaard, 1999). As in activated sludge systems, the MBBR uses the entire volume of the reactor for microbial growth. Instead of freely suspended microorganisms, the majority of the MBBR's microorganisms are attached to a submerged media. As in biofilm reactors, such as trickling filters, the MBBR does not require any recycling of sludge as in activated sludge processes. The MBBR within the Mote IAS had a total volume of 72.61 m^3 . Kaldnes carriers (Furenest, Norway) with a surface area to volume ratio of $350 \text{ m}^2/\text{m}^3$ were used as the media for biofilm growth. Hem et al. (1993) found that in aerated MBBRs, the constant mixing caused by air bubbles are so turbulent that one can assume the MBBR is completely mixed. In the Mote IAS, the MBBR was constantly aerated. A UV system disinfected the water to inactivate any harmful bacteria prior to the fish tank.

It was assumed that there was no degradation of PON or DON in the MBBR. MBBRs have the ability to remove high organic loading rates from municipal wastewater (Rusten et al., 2006). However, in aquaculture, the objective of the MBBR is to nitrify ammonium (Rusten et al., 2006). At high organic loading rates, heterotrophic bacteria will compete with nitrifiers; thus aquaculture MBBRs typically operate with low organic loading rates. It was assumed that the only nitrogen transformation occurring within the MBBR was the oxidation of $\text{NH}_4^+\text{-N}$ to $\text{NO}_3^-\text{-N}$ via biological nitrification. Mass balances on PON, DON, $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ in the MBBR are given as:

$$V_{\text{MB}} \frac{dC_{7\text{P}}}{dt} = f_{10\text{P}} Q_{10} C_{10\text{P}} - Q_7 C_{7\text{P}} \quad (25)$$

$$V_{\text{MB}} \frac{dC_{7\text{D}}}{dt} = f_{10\text{D}} Q_{10} C_{10\text{D}} - Q_7 C_{7\text{D}} \quad (26)$$

$$V_{\text{MB}} \frac{dC_{7\text{A}}}{dt} = f_{10\text{A}} Q_{10} C_{10\text{A}} - r_{\text{MBni}} V_{\text{MB}} - Q_7 C_{7\text{A}} \quad (27)$$

$$V_{\text{MB}} \frac{dC_{7\text{N}}}{dt} = f_{10\text{N}} Q_{10} C_{10\text{N}} + r_{\text{MBni}} V_{\text{MB}} - Q_7 C_{7\text{N}} \quad (28)$$

where V_{MB} is volume of the MBBR (L) and r_{MBni} is the rate of nitrification in the MBBR ($\text{mg/L}\cdot\text{day}$).

The rate of nitrification in the MBBR is given by:

$$r_{\text{MBni}} = Na \quad (29)$$

$$N = k_{\text{MBni}} C_{6\text{A}} L_{\text{B}} \beta \quad (30)$$

where N is the liquid phase $\text{NH}_4^+\text{-N}$ flux to the biofilm ($\text{mg}/\text{m}^2\cdot\text{day}$), a is the surface area per volume of the media in the MBBR (m^2/m^3), $C_{6\text{A}}$ is the liquid phase $\text{NH}_4^+\text{-N}$ concentration in the MBBR (mg/L), k_{MBni} is the first order nitrification rate coefficient in the MBBR ($1/\text{day}$), L_{B} is the thickness of the biofilm in the MBBR (m) and β is a biofilm constant involving the $\text{NH}_4^+\text{-N}$

diffusion constant, the length of the biofilm and the reaction rate (unitless). Equations 29 and 30 were adapted from Eweis et al. (1998) on modeling biofilters for biological treatment.

3.3.5 South Plant Raceway Mass Balance

The south plant raceway was assumed to act similar to a constructed wetland. As a complex system, constructed wetlands use various processes to remove nutrients and solids from the water (US EPA, 2000). Some of the nutrient removal processes include sedimentation, adsorption, plant uptake and biodegradation (Tucker et al., 2008). Another assumption was that the plant raceway acted as a completely mixed flow reactor. A recirculation pump recirculated the water from the end of the plant raceway back to the front of the plant raceway, allowing for the plant raceway to be completely mixed. All processes were assumed to operate under first order reaction rates based upon the low concentrations observed in the effluent. Biological processes can be modeled using first order kinetics; when concentrations are much less than the half saturation constants ($C \ll K_s$ where K_s is the half saturation constant). The observed NH_4^+ -N concentration in the plant raceway was as low as 0.1 mg/L, while the K_s for nitrification ranges between 0.5 to 1.0 mg/L (Metcalf and Eddy, 2003). Similarly, the observed NO_3^- -N concentration reached as low as 0.1 mg/L, while the K_s for denitrification ranges between 0.2 to 0.5 mg/L (Henze et al., 2002). Kadlec and Wallace (2009) also described typical constructed wetlands as operating under first order reaction rates.

A mass balance on PON in the south plant raceway is given by:

$$V_{PR} \frac{dC_{2P}}{dt} = \frac{1}{3} Q_1 C_{1P} - r_{hyd} V_{PR} - r_{sed} V_{PR} - r_{acc} V_{PR} - Q_2 C_{2P} \quad (31)$$

where V_{PR} is the volume of the plant raceway (L), r_{hyd} is the rate of hydrolysis (mg/L*day), r_{sed} is the rate of PON sedimentation in the plant raceway (mg/L*day) and r_{acc} is the rate of PON

accumulation in the soil of the plant raceway (mg/L*day). The flow entering the south plant raceway was only one third of the solids tank effluent flow rate. As mentioned previously, it was assumed that the flow was equally distributed from the solids tank to the south and north plant raceway and the geotube.

Hydrolysis is the process of converting PON to DON. Equations 32 and 33 were developed by Henze and Mladenovski (1991), who described the rate of hydrolysis of PON under different oxygen conditions at 20°C in batch reactors seeded with raw municipal wastewater as:

$$r_{\text{hyd}} = k_{\text{hyd}}C_{2P} \quad (32)$$

$$k_{\text{hyd}} = 0.06e^{-0.2(20-T)} \quad (33)$$

where k_{hyd} was a rate constant dependent upon temperature (1/day).

The soil accumulation term describes the amount of PON in the soil when plants were harvested. Equation 34 describes the rate of PON soil accumulation:

$$r_{\text{acc}}V_{\text{PB}} = f_{\text{acc}}Q_2C_{2P} \quad (34)$$

where f_{acc} is the fraction of PON in the plant soil. A value of 0.0093 was used for f_{acc} and was determined by Boxman (2013).

Sedimentation is the physical removal of particulates (Kadlec and Wallace, 2009). In the IAS, sedimentation occurs underneath the plant trays, where the particulates are trapped. This layer of sedimentation on the bottom of the plant raceways remained in the system until it was manually removed. Mayo and Mutamba (2005) and Kadlec and Wallace (2009) used equations involving the Reynolds number, gravity and density of the particulates. Given the complexities of those equations, a simple estimate of the fraction of nitrogen, in the sediments was used instead. The rate of PON sedimentation is given by:

$$r_{\text{sed}}V_{\text{PB}} = f_{\text{sed}}Q_2C_{2\text{P}} \quad (35)$$

where f_{sed} is the fraction of PON found in the sediments. A value of 0.05 was used for f_{sed} and was determined by Boxman (2013).

A mass balance on DON in the south plant raceway is given by:

$$V_{\text{PR}} \frac{dC_{2\text{D}}}{dt} = \frac{1}{3}Q_1C_{1\text{D}} + r_{\text{hyd}}V_{\text{PR}} - r_{\text{mi}}V_{\text{PR}} - Q_2C_{2\text{D}} \quad (36)$$

Mineralization was described in the solids tank mass balance (Equations 22 and 23).

A mass balance on NH_4^+ -N in the south plant raceway is given by:

$$V_{\text{PB}} \frac{dC_{2\text{A}}}{dt} = \frac{1}{3}Q_1C_{1\text{A}} + r_{\text{mi}}V_{\text{PB}} - r_{\text{up1}}V_{\text{PB}} - r_{\text{ni}}V_{\text{PB}} - Q_2C_{2\text{A}} \quad (37)$$

where r_{up1} is the rate of plant uptake of NH_4^+ -N (mg/L*day) and r_{ni} is the rate of nitrification in the plant raceway (mg/L*day).

The rate of plant uptake of NH_4^+ -N is given by:

$$r_{\text{up1}}V_{\text{PB}} = f_{\text{up}}Q_2C_{2\text{A}}P_1 \quad (38)$$

where F_{up1} was the fraction of the TN concentration taken up by plants and P_1 was the preference factor for NH_4^+ -N. A value of 2.12 was used for F_{up1} . F_{up1} was described by Boxman (2013) when the TN per plant mass in the south plant raceway was determined. However, since Boxman (2013) was unable to differentiate between the amount of NH_4^+ -N and NO_3^- -N in the plants, a preference factor was included. Kadlec and Wallace (2009) stated that NH_4^+ -N would be the preferred nitrogen species because plants would need to reduce NO_3^- -N before it could be used for biosynthesis. Thus, the initial assumption used was that the preference factor for NH_4^+ -N was higher than NO_3^- -N.

The rate of nitrification in the plant raceways was assumed to follow first order reaction kinetics and is given by:

$$r_{\text{ni}} = k_{\text{ni}}C_{2\text{A}} \quad (39)$$

$$k_{ni} = [k_1 X_{ni}] * \left[\frac{C_{DO}}{K_{DO} + C_{DO}} \right] * \left[\frac{14200}{14200 + C_{salt}} \right] * [\theta^{T-20}] \quad (40)$$

$$k_1 = \frac{\hat{\mu}_{ni}}{Y_{ni} * K_{ni}} \quad (41)$$

where k_{ni} is the first order nitrification rate in the plant raceway (1/day), k_1 is a nitrifier constant (L/mg*day), $\hat{\mu}_{ni}$ is the max specific growth rate for nitrifiers (1/day), X_{ni} is the active biomass for nitrifiers (mg/L), Y_{ni} is the yield coefficient for nitrifiers (g biomass/g NH_4^+ -N), K_{ni} is the half saturation constant for nitrifiers (mg/L), C_{DO} is the DO concentration in the plant raceway (mg/L), K_{DO} is the half saturation constant for DO (mg/L), C_{salt} is the salt concentration (mg/L) and θ is the Arrhenius constant (unitless).

In constructed wetlands, DO can be supplied by physical transfer, plant transfer or by mechanical aeration (Kadlec and Wallace, 2009). In the Mote IAS, there were no aerators in the plant raceways. Emergent plants will release DO near their roots for their own biological processes, but this additional oxygen is not enough to contribute to the overall system (Kadlec and Wallace, 2009). Physical transfer processes include any interaction between the atmosphere and the water such as turbulence from a river or wind. Temperature also influences the gas transfer rate of DO. Equation 42 was developed by Elmore and Hayes (1960), where temperature impacted the DO concentration at 1 atmosphere:

$$C_{DO} = 14.652 - 0.41022T + 0.007991T^2 - 0.00007777T^3 \quad (42)$$

A mass balance on NO_3^- -N in the plant raceway is given by:

$$V_{PB} \frac{dC_{2N}}{dt} = \frac{1}{3} Q_1 C_{1N} + r_{ni} V_{PB} - r_{up2} V_{PB} - r_{de} V_{PB} - Q_2 C_{2N} \quad (43)$$

where r_{up2} is the rate of plant uptake of NO_3^- -N (mg/L*day) and r_{de} is the rate of denitrification (mg/L*day) in the plant raceway.

The rate of plant uptake of NO_3^- -N is given by:

$$r_{up2}V_{PB} = f_{up}Q_2C_{2N}P_2 \quad (44)$$

$$P_1 + P_2 = 1 \quad (45)$$

where P_2 is the preference factor of plant uptake for NO_3^- -N. Equation 44 is the same equation as Equation 38 except that the preference factor is expected to be lower for NO_3^- -N. The preference factor can be adjusted for other models if the plant species favors one form of nitrogen over the other.

The rate of denitrification is assumed to follow first order reaction kinetics and is given by:

$$r_{de} = k_{de}C_{2N} \quad (46)$$

$$k_{de} = [k_2X_{de}] * \left[\frac{C_{COD}}{K_{COD} + C_{COD}} \right] * \left[\frac{15200}{15200 + C_{salt}} \right] * [\theta^{T-20}] \quad (47)$$

$$k_2 = \frac{\hat{\mu}_{de}}{Y_{de} * K_{de}} \quad (48)$$

where k_{de} is the first order denitrification constant (1/day), k_2 is a denitrifier constant (L/mg*day), $\hat{\mu}_{de}$ is the max specific growth rate of the denitrifiers (1/day), X_{de} is the active biomass of denitrifiers (mg/L), Y_{de} is the yield coefficient of denitrifiers (g biomass/g NO_3^- -N), K_{de} is the half saturation constant for NO_3^- -N (mg/L), C_{COD} is the COD concentration (mg/L) and K_{COD} is the half saturation constant for COD (mg/L). DO inhibits denitrification at concentrations above 0.3-1.5 mg/L (Kadlec and Wallace, 2009), but was not included in Equation 47. The observed bulk influent and effluent DO concentrations of the south plant raceway indicated an increase of DO through the plant raceway, with an average observed DO concentration of 1.9 mg/L (Boxman, 2013). However, sampling within the plant raceway, using the Quanta Hydrolab multimeter probe showed there were locations in the middle of the plant raceway where there were low enough DO concentrations for denitrification (Boxman, 2013). Within the south plant raceway, the average DO concentration was 0.17 mg/L (Boxman, 2013).

3.3.6 Sand Filter Mass Balance

Unlike the south plant raceway, the north plant raceway incorporated a sand filter for solids removal. Only ammonification was modeled in the sand filter and no other physical, chemical or biological removal mechanisms were included. Using the laboratory data presented by Kruglick (2012) and Boxman (2013), $\text{NH}_4^+\text{-N}$ was the only nitrogen species to increase through the sand filter. This was assumed to be due to ammonification of DON. Ammonification in the sand filter followed Equations 22 and 23. Mass balances for the sand filter are given by:

$$V_{\text{SF}} \frac{dC_{5\text{P}}}{dt} = \frac{1}{3} Q_1 C_{1\text{P}} - f_{5\text{P}} \frac{1}{3} Q_1 C_{1\text{P}} - Q_5 C_{5\text{P}} \quad (49)$$

$$V_{\text{SF}} \frac{dC_{5\text{D}}}{dt} = \frac{1}{3} Q_1 C_{1\text{D}} - r_{\text{mi}} V_{\text{SF}} - Q_5 C_{5\text{D}} \quad (50)$$

$$V_{\text{SF}} \frac{dC_{5\text{A}}}{dt} = \frac{1}{3} Q_1 C_{1\text{A}} + r_{\text{mi}} V_{\text{SF}} - Q_5 C_{5\text{A}} \quad (51)$$

$$V_{\text{SF}} \frac{dC_{5\text{N}}}{dt} = \frac{1}{3} Q_1 C_{1\text{N}} - f_{5\text{N}} \frac{1}{3} Q_1 C_{1\text{N}} - Q_5 C_{5\text{N}} \quad (52)$$

where V_{SF} is the volume of the sand filter (L), $C_{5\text{P}}$ is the PON concentration in the sand filter (mg/L), $f_{5\text{P}}$ is the fraction of PON removed by the sand filter, $C_{5\text{D}}$ is the DON concentration in the sand filter (mg/L), $C_{5\text{A}}$ is the $\text{NH}_4^+\text{-N}$ concentration in the sand filter (mg/L), $C_{5\text{N}}$ is the $\text{NO}_3^-\text{-N}$ concentration in the sand filter (mg/L) and $f_{5\text{N}}$ is the fraction of $\text{NO}_3^-\text{-N}$ removed by the sand filter.

3.3.7 North Plant Raceway Mass Balance

The north plant raceway used the same equations as the south plant raceway with two differences. First, the influent of the south plant raceway was from the solids tank while the influent from the north plant raceway was from the sand filter. Another difference was the PON

accumulation and sedimentation. The sand filter removed most of the PON, thus decreasing the constants used in those equations.

3.3.8 Geotube Mass Balance

The last third of the flow was treated by a mesh bag called a geotube. The geotube was a commercially purchased product from Ten Cate Nicolon, Commerce, GA. In the Mote IAS, the geotube was approximately 3m in length by 3m in width and had the capability of growing to a height of 1.5m once full. The physical, chemical and biological removal mechanisms occurring in the geotube were not modeled. Data taken from Kruglick (2012) and Boxman (2013) provided a range of removal efficiencies. Average removal efficiencies were used for each nitrogen species to simulate the geotube and are given by:

$$V_{GE} \frac{dC_{4P}}{dt} = \frac{1}{3} Q_1 C_{1P} - f_{4P} \frac{1}{3} Q_1 C_{1P} - Q_2 C_{4P} \quad (53)$$

$$V_{GE} \frac{dC_{4D}}{dt} = \frac{1}{3} Q_1 C_{1D} - f_{4D} \frac{1}{3} Q_1 C_{1D} - Q_2 C_{4D} \quad (54)$$

$$V_{GE} \frac{dC_{4A}}{dt} = \frac{1}{3} Q_1 C_{1A} - f_{4A} \frac{1}{3} Q_1 C_{1A} - Q_2 C_{4A} \quad (55)$$

$$V_{GE} \frac{dC_{4N}}{dt} = \frac{1}{3} Q_1 C_{1N} - f_{4N} \frac{1}{3} Q_1 C_{1N} - Q_2 C_{4N} \quad (56)$$

where V_{GE} is the volume of the geotube (L), f_{4P} is the fraction of PON removed by the geotube, f_{4D} is the fraction of DON removed by the geotube, f_{4A} is the fraction of NH_4^+ -N removed by the geotube and f_{4N} is the fraction of NO_3^- -N removed by the geotube.

3.4 Initial Conditions

Although fish feed and fish growth data recording began in November 2010, no water quality data was available for that month. The experimental plan was to let the system stabilize

before the first sample collection. The first data set (1 March 2011) was used as the initial nitrogen concentrations (Boxman, 2013). The model begins to predict nitrogen concentrations on day 120, which simulates 1 March 2011.

3.5 STELLA™

STELLA™ is an easy to use computer program for dynamic model building and has been used in various biological and environmental models (Ouyang, 2008). STELLA™ allows the user to build a model by drawing a diagram (ISEE, 2013). The integration method selected was Euler's Method, with a time step size of 0.25. The unit of time is in days. The run and interaction modes are selected as normal. The equations from the south plant raceway and the MBBR were evaluated first in Microsoft Excel under static conditions. A detailed explanation of the check is located in Appendix C. Dr. Sarina Ergas at the University of South Florida has a copy available for anyone who would like a copy. She can be reached by email at sergas@usf.edu or by at phone 813-974-1119. All the equations used in STELLA™ are listed in Appendix D.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Calibration

Three types of parameters were used in the model (Table 4-1): experimental, literature and calibrated. Experimental data was used to estimate the plant uptake of TN, soil accumulation of PON and soil sedimentation of PON. Details of these experiments were given by Kruglick (2012) and Boxman (2013). Literature values were used for biokinetic parameters: the half saturation constants for denitrification, nitrification, DO and heterotrophic metabolism, the maximum specific growth rate for denitrifiers and nitrifiers, the MBBR first order reaction rate constant as well as the yield coefficients for denitrifiers and nitrifiers. Literature values were from studies of biological processes at wastewater treatment plants or constructed wetlands. Each literature value was given as a range of values and calibration was done only within this range. Finally, the completely calibrated values were the fraction of active biomass for denitrifiers and nitrifiers, fractions of nitrogen in waste as uneaten feed, fish waste as DON and fish waste as $\text{NH}_4^+\text{-N}$, preference factors for plant uptake of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$. Calibrated parameters values were adjusted manually until the model's output was a best fit to the observed data by minimizing the sum of the squared residuals.

Table 4-1. Parameters used in the model. *Details on methods used for experimentally determined parameters are provided in Boxman (2013).

Variable	Description of parameters	Literature range	Source	Value used in model
f_A	Fraction of nitrogen in waste as NH_4^+ -N	---	Calibrated	0.504
f_{acc}	Fraction of PON accumulated in plant soil	---	Experimental	0.93
f_D	Fraction of nitrogen in waste as DON	---	Calibrated	0.056
f_{de}	Fraction of active biomass for denitrifiers	---	Calibrated	0.25
f_{ni}	Fraction of active biomass for nitrifiers	---	Calibrated	0.12
f_p	Fraction of nitrogen in waste as uneaten feed	---	Calibrated	0.14
f_{sed}	Fraction of PON in sediments	---	Experimental	0.05
f_{up}	Fraction of TN taken up by plants	---	Experimental	0.0212
f_{VSS}	Fraction of feed as VSS	---	Calibrated	$10^{-4.25}$
k_{MBni} (1/day)	MBBR first order reaction rate constant	0.5	Rusten et al (2006)	0.5
K_{COD} (mg/L)	Half saturation constant for heterotrophic metabolism	10 – 20	Henze et al (2002)	10
K_{de} (mg/L)	Half saturation constant for denitrification	0.2 – 0.5	Henze et al (2002)	0.2
K_{DO} (mg/L)	Half saturation constant for DO	0.5 – 1.0	Henze et al (2002)	0.7
K_{ni} (mg/L)	Half saturation constant for ammonium	0.5 – 1.0	Metcalf and Eddy (2003)	0.75
P_1	Preference factor of plant uptake for NH_4^+ -N	---	Calibrated	0.50
P_2	Preference factor of plant uptake for NO_3^- -N	---	Calibrated	0.50
$\hat{\mu}_{\text{de}}$ (1/day)	Maximum specific growth rate for denitrifiers	0.015	Wynn and Liehr (2001)	0.015
$\hat{\mu}_{\text{ni}}$ (1/day)	Maximum specific growth rate for nitrifiers	0.1	Wynn and Liehr (2001)	0.01
Y_{de} (g/g)	Yield coefficient for denitrifiers	0.25	Rittman and McCarty (2001)	0.25
Y_{ni} (g/g)	Yield coefficient for nitrifiers	0.1 – 0.15	Metcalf and Eddy (2003)	0.1

The VSS concentration was an important parameter because it determined the active biomass concentration for nitrifiers and denitrifiers. Rather than creating a model component involving the active biomass life cycle, it was assumed that the active biomass was a fraction of the VSS. The VSS concentration was a function of the feed rate, as shown in Figure 4-1.

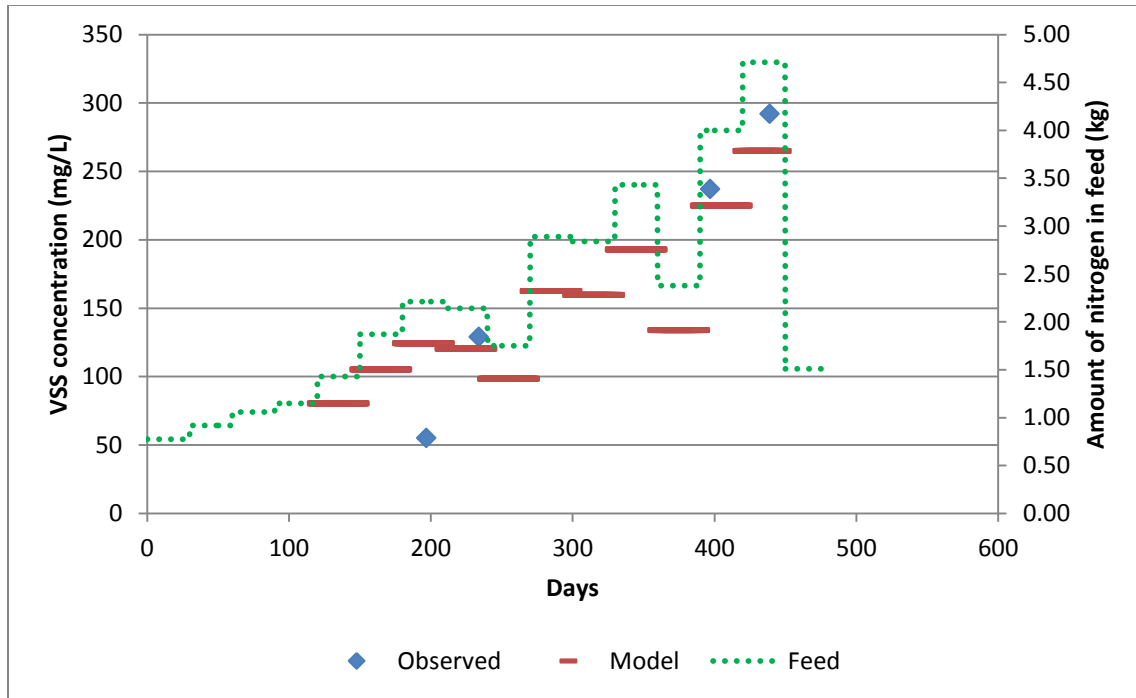


Figure 4-1. Observed and modeled VSS concentrations.

Another important parameter was the maximum specific growth rate for nitrifiers and denitrifiers (Equations 41 and 48). These parameters fell outside the literature range for wastewater treatment plants, ranging from one to two orders of magnitude lower in constructed wetlands. According to Wynn and Liehr (2001), some of the microorganism parameters needed to be lowered beyond the wastewater treatment plants literature range in their constructed wetland model. Wynn and Liehr (2001) hypothesized that the literature range was for conventional wastewater systems where microorganisms were growing under ideal conditions.

Within a constructed wetland, the growth conditions are slowed perhaps due to diffusion through the soil's pore spaces and by the low substrate concentrations. Kadlec and Wallace (2009) did not provide ranges for maximum specific growth rates but bring up the point that conditions in conventional wastewater treatment plants do not also apply to constructed wetlands. For instance, the DO and alkalinity needed for nitrification and denitrification are lower in constructed wetlands than in wastewater treatment plants. These areas need further investigation.

4.2 Sensitivity Analysis

A sensitivity analysis was performed to determine how sensitive the model output was to variations in model parameters. Sensitivity analysis can also help identify where future research should be conducted (Jamu and Piedrahita, 2002b). One parameter that has already been mentioned is the maximum specific growth rate of the nitrifiers and denitrifiers. The maximum specific growth rates are outside the literature range for wastewater treatment plants and warrant further investigation in constructed wetlands. The sum of the squared residuals was calculated by comparing the model output to the observed data for each sample day, averaged together for the four different sample locations, then averaged all together to represent how the system was effected.

The biological constants used in nitrification (k_1 , Equation 41) and denitrification (k_2 , Equation 48) were varied only by the half saturation constants of nitrifiers and denitrifiers. As k_1 decreased, the sum of the squared residuals doubles (Table 4-2). However, since the $\text{NH}_4^+\text{-N}$ concentration was low, there was very little overall change in the model's concentration output of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$. As k_2 decreased, it caused a huge difference in the model output; the

sum of the square residuals nearly doubles (Table 4-3). Unlike $\text{NH}_4^+\text{-N}$, the $\text{NO}_3^-\text{-N}$ concentration is large enough that any small changes to the biological constant, causes huge differences between the model output and the observed data.

Table 4-2. Sum of squared residuals for the nitrifier constant (k_1) with respect to the $\text{NH}_4^+\text{-N}$ concentration at different sample locations (Figure 3-1). Only the half saturation constant for nitrifiers was varied. The larger the sum of squared residuals, the less accurate the model output is.

k_1 (L/mg*day)	W2 (mg^2/L^2)	W3 (mg^2/L^2)	W6 (mg^2/L^2)	W7 (mg^2/L^2)	Average (mg^2/L^2)
2.0	0.00792	0.0205	0.00293	0.00198	0.00832
1.7	0.0110	0.0277	0.00308	0.00198	0.0110
1.4	0.0126	0.0352	0.00213	0.00164	0.0129
1.1	0.0172	0.0469	0.00213	0.00225	0.0171

Table 4-3. Sum of squared residuals for the denitrifier constant (k_2) with respect to the $\text{NO}_3^-\text{-N}$ concentration at different sample locations (Figure 3-1). Only the half saturation constant for denitrifiers was varied. The larger the sum of squared residuals, the less accurate the model output is.

k_2 (L/mg*day)	W2 (mg^2/L^2)	W3 (mg^2/L^2)	W6 (mg^2/L^2)	W7 (mg^2/L^2)	Average (mg^2/L^2)
0.3	10.51	3.40	1.49	1.57	4.24
0.2	19.2	5.94	1.55	1.68	7.09
0.15	33.7	9.81	11.7	11.8	16.5
0.12	59.4	16.3	26.1	28.2	32.49

When the fraction of VSS for nitrifiers and denitrifiers were varied, changes in the denitrifier fraction resulted in large differences in the model output. The $\text{NH}_4^+\text{-N}$ concentration was low throughout the study, so varying the nitrifier fraction did not affect the overall sum of the squared residuals. However, the $\text{NO}_3^-\text{-N}$ concentration was high enough that by varying the denitrifier fraction, there was a noticeable change in the sum of the square residuals (Table 4-4).

Table 4-4. Sum of squared residuals as a function of the denitrifier fraction of VSS (f_{de}) with respect to the NO_3^- -N concentration at different sample locations (Figure 3-1). The larger the sum of squared residuals, the less accurate the model output is.

f_{de}	W2 (mg^2/L^2)	W3 (mg^2/L^2)	W6 (mg^2/L^2)	W7 (mg^2/L^2)	Average (mg^2/L^2)
0.06	34.5	10.0	11.1	12.1	16.9
0.12	10.6	3.45	1.45	1.54	4.27
0.2	4.92	1.59	8.58	9.54	6.16
0.26	3.07	0.984	12.4	13.7	7.54

The model was not sensitive to changes in the preference factors for plant uptake (Tables 4-5 and 4-6). Schulz et al. (2003) mentioned that the emergent plants in a constructed wetland have a minor impact on the overall nitrogen removal process. Instead, the plants play an important role in creating the environment necessary for an effective treatment strategy. Boxman (2013) also suggested that plants have a minor role in nitrogen removal.

Table 4-5. Sum of square residuals for the NH_4^+ -N preference factor at different sample locations. The larger the sum of squared residuals, the less accurate the model output is.

Preference factor of plant uptake for NH_4^+ -N	W2 (mg^2/L^2)	W3 (mg^2/L^2)	W6 (mg^2/L^2)	W7 (mg^2/L^2)	Average (mg^2/L^2)
0.25	0.0125	0.0343	0.0021	0.0017	0.0127
0.50	0.0125	0.0343	0.0021	0.0017	0.0127
0.75	0.0125	0.0343	0.0021	0.0017	0.0127

Table 4-6. Sum of square residuals for the NO_3^- -N preference factor at different sample locations. The larger the sum of squared residuals, the less accurate the model output is.

Preference factor of plant uptake for NO_3^- -N	W2 (mg^2/L^2)	W3 (mg^2/L^2)	W6 (mg^2/L^2)	W7 (mg^2/L^2)	Average (mg^2/L^2)
0.25	10.64	3.43	1.45	5.79	4.27
0.50	10.51	3.40	1.49	5.78	4.24
0.75	10.46	3.39	1.50	5.78	4.24

4.3 Model Verification

To determine how closely the model resembles the observed data, model verification evaluated if the model output was within one standard deviation of the observed mean. The model was within one standard deviation of the observed mean at all locations for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ with the exception of the sand filter (W5) for $\text{NO}_3^-\text{-N}$ (Figures 4-2 and 4-3). One explanation is that there were biological, chemical and physical processes occurring in the sand filter that was not captured by the model.

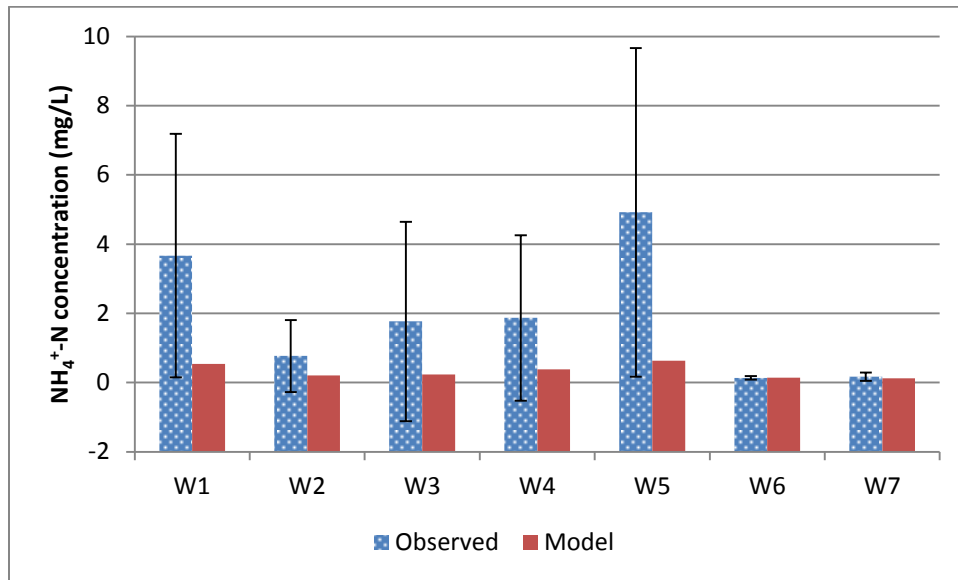


Figure 4-2. Comparison between the average observed and average model concentrations for $\text{NH}_4^+\text{-N}$ at each sample location. Error bars represent plus or minus one standard deviation of the observed mean.

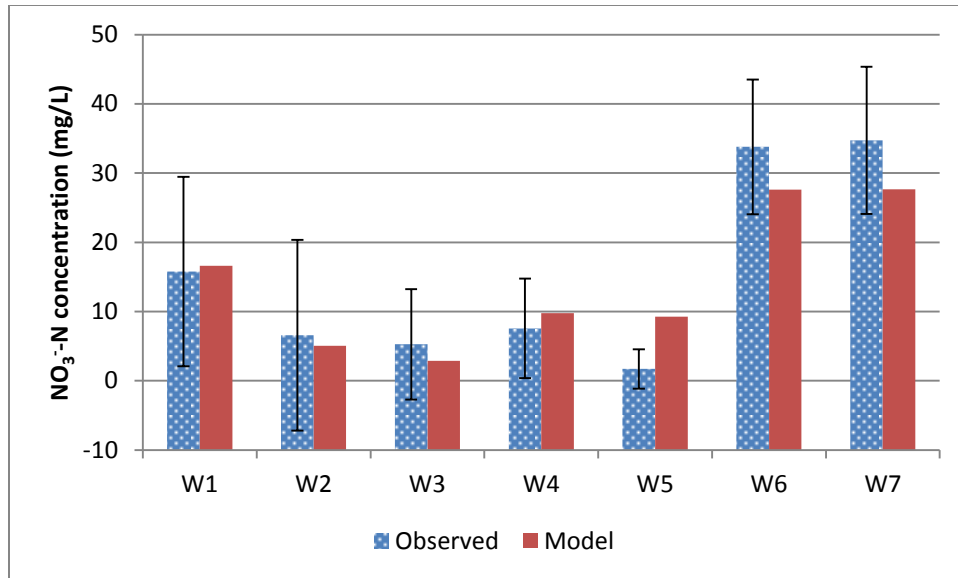


Figure 4-3. Comparison between the average observed and average model concentrations for NO_3^- -N at each sample location. Error bars represent plus or minus one standard deviation of the observed mean.

4.4 MBBR

The MBBR was the last treatment process prior to the fish tank. It was important for the MBBR to reduce the NH_4^+ -N concentration to levels low enough as to not become toxic to the fish. For marine fish, NH_4^+ -N concentrations higher than 1.86 mg/L are deadly (Randall and Tsui, 2002). Nitrification represented the only nitrogen removal process for NH_4^+ -N in the MBBR. The observed average MBBR influent NH_4^+ -N concentration was 0.13 mg/L and the model average influent concentration was 0.14 mg/L (Figure 4-4). Observed average MBBR effluent NH_4^+ -N concentration was 0.17 mg/L and the model average effluent concentration was 0.10 mg/L (Figure 4-5). Of the observed concentrations, the 3 December 2011 data point was unusually high when compared to the others. This data point reflects the complete opposite of what was expected; the NH_4^+ -N concentration decreases through the MBBR, not increases. If that data point was removed, the average observed effluent NH_4^+ -N concentration was 0.12 mg/L, representing a decrease through the MBBR, which was expected. On average, the

ammonium removal efficiency based on the observed data was 8% while the model predicted 11% removal.

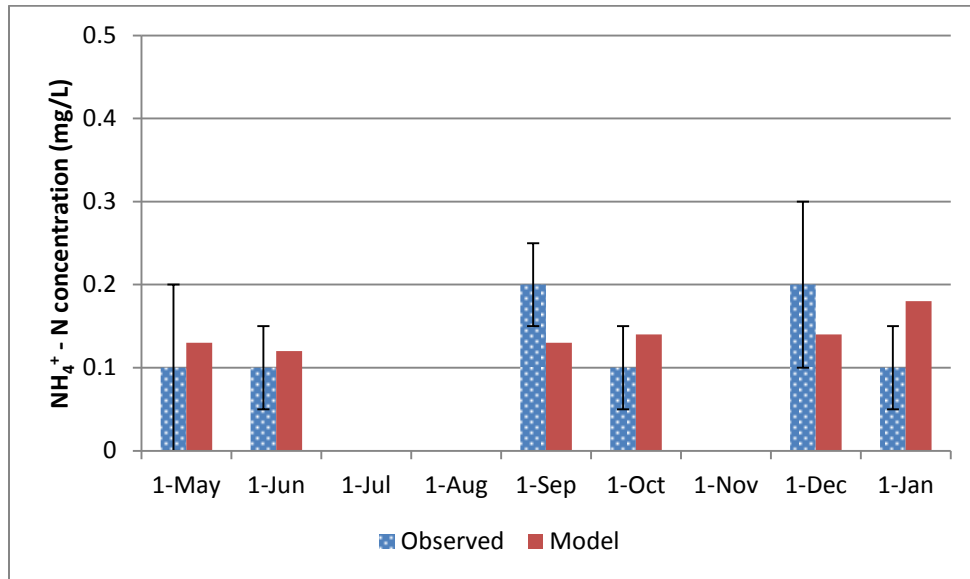


Figure 4-4. Influent NH₄⁺-N concentration of the MBBR (W6).

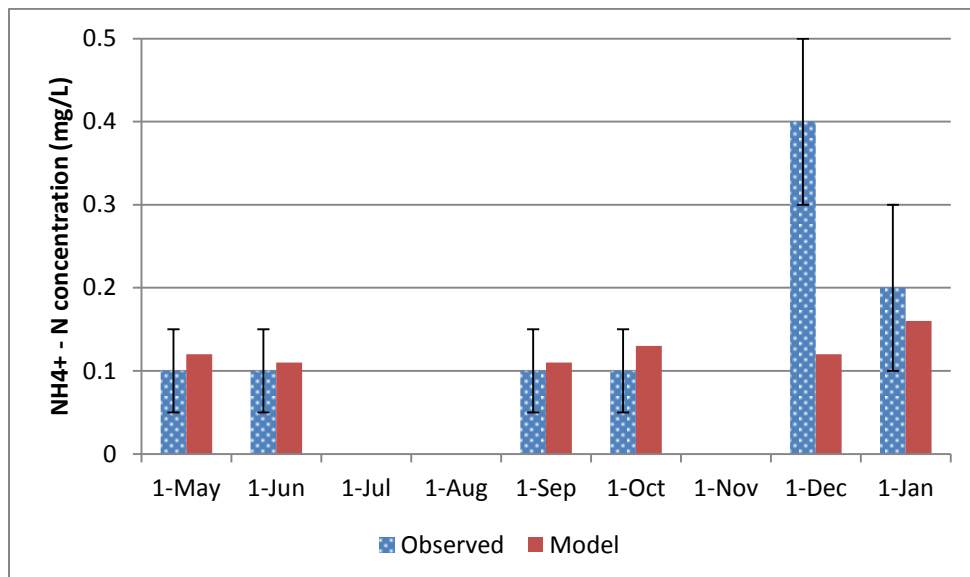


Figure 4-5. Effluent NH₄⁺-N concentration from the MBBR (W7).

Although fish are not as sensitive to NO_3^- -N as ammonium, at high concentrations, NO_3^- -N can be dangerous to fish. Periodically, a RAS needs to exchange its water to maintain a moderate NO_3^- -N concentration in RAS if a denitrification component is not included. However, in the Mote IAS and in the model, it is clearly visible that NO_3^- -N is removed even though denitrification is not occurring in the MBBR (Figures 4-6 and 4-7). On average, the observed data showed a 3% increase of NO_3^- -N through the MBBR while the model showed an increase of 0.5%. Reduction of NO_3^- -N in the overall system was occurring in the plant raceways, geotube and solids tank.

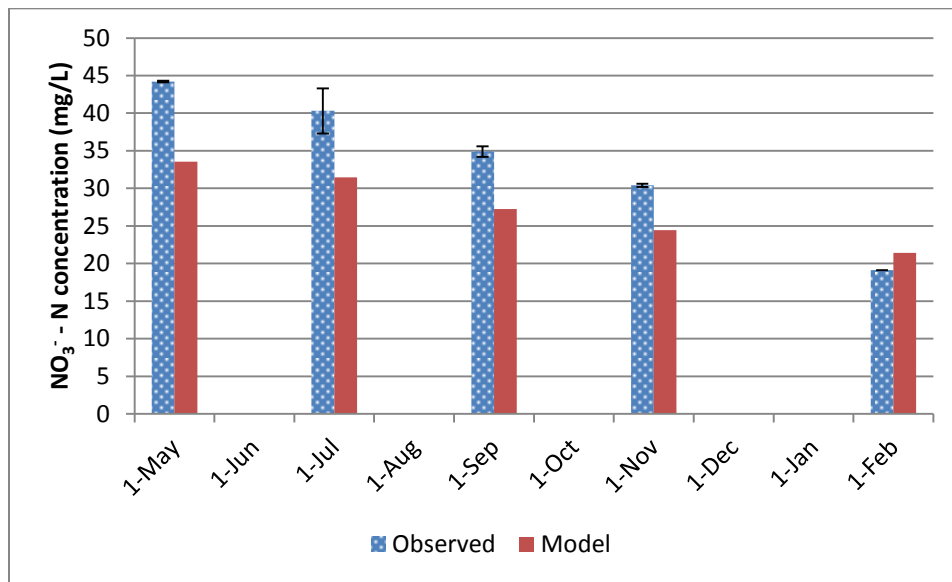


Figure 4-6. Influent NO_3^- -N concentration of the MBBR (W6).

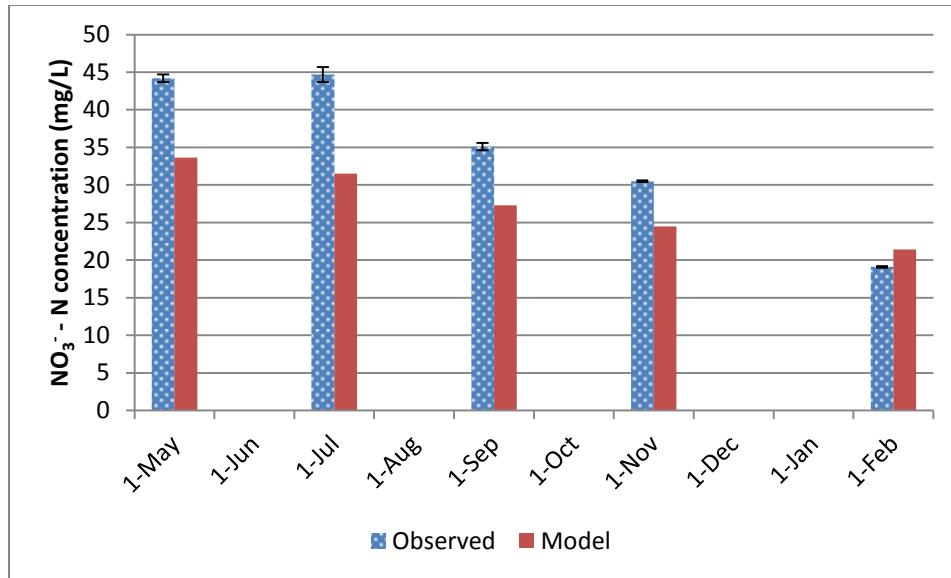


Figure 4-7. Effluent NO_3^- -N concentration from the MBBR (W7).

4.5 South Plant Raceway

The south plant raceway received waste directly from the solids tank. The model predicted an average effluent NH_4^+ -N concentration of 0.24 mg/L compared to the observed average of 0.77 mg/L (Figure 4-8). The low model output NH_4^+ -N concentration was likely caused by the low NH_4^+ -N concentration from the solids tank. The solids tank was not thoroughly modeled using the physical, biological and chemical processes present. In addition, the high observed values on 15 October 2011 and 3 December 2011 could have been due to variations in flow rates. The model was constructed assuming that the flow from the solids tank was divided evenly between the two plant raceways and the geotube. However, in reality, the flow from the solids tank was not always divided evenly between the three. At times, the pipe entering the south plant raceway was clogged, causing little to no flow into the south plant raceway. On average, the NH_4^+ -N removal efficiency based on the observed data was 79% while the model predicted 51% removal.

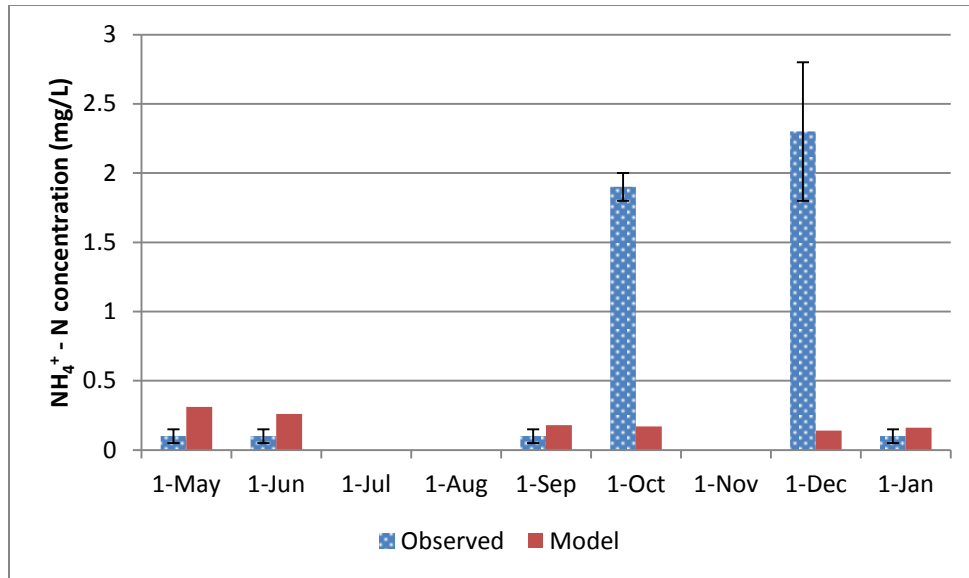


Figure 4-8. Effluent $\text{NH}_4^+\text{-N}$ concentration from the south plant raceway (W2).

Significant $\text{NO}_3^-\text{-N}$ removal occurred in the south plant raceway (Figure 4-9). Although bulk measurements of DO concentration in the south plant raceway ranged as high as 5.5 mg/L (Boxman, 2013), DO concentrations measured underneath the plant trays showed that DO concentrations were less than 0.20 mg/L (Boxman, 2013). Kadlec and Wallace (2009) also mention that denitrification occurs in underwater sediment surfaces. On 24 May 2011, the observed $\text{NO}_3^-\text{-N}$ concentration was extremely large compared to the other sample days. Since the flow clogged on occasion, the physical removal of the sediments in the south plant raceway would have added additional DO and removed a portion of the denitrifier population during the process, limiting denitrification. On average, the model effluent $\text{NO}_3^-\text{-N}$ concentration was 5.1 mg/L while the average observed $\text{NO}_3^-\text{-N}$ concentration was 6.6 mg/L. $\text{NO}_3^-\text{-N}$ removal efficiency in the south plant raceway was 69% for the model compared to 58% for the observed data.

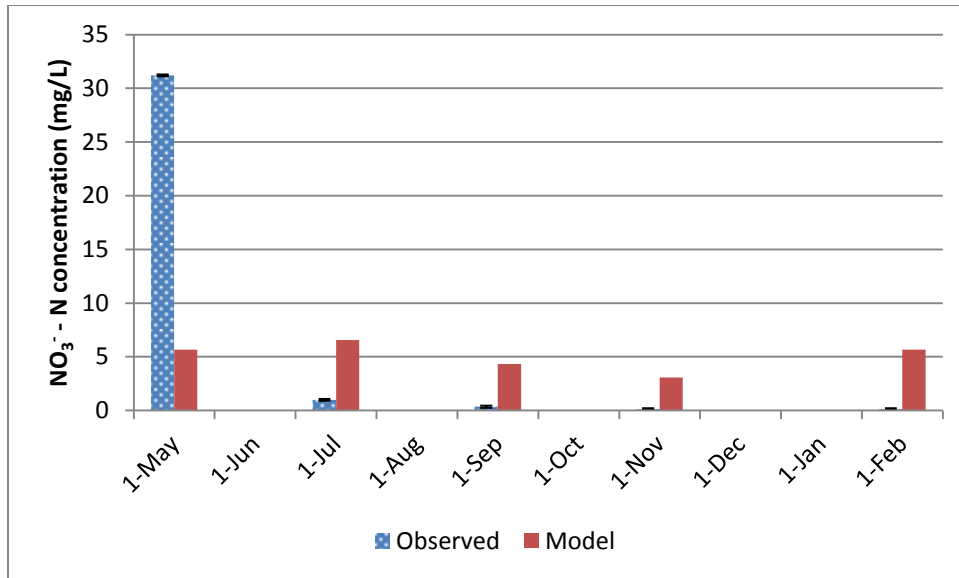


Figure 4-9. Effluent NO_3^- -N concentration from the south plant raceway (W2).

4.6 North Plant Raceway

The north plant raceway differed from the south plant raceway in that the effluent from the solids tank first flowed through a sand filter. Like the solids tank, the sand filter was not thoroughly modeled for physical, biological and chemical processes. The north plant raceway used the same equations and parameters as described in the south plant raceway. The model predicted an average effluent NH_4^+ -N concentration of 0.27 mg/L compared to the observed average of 1.77 mg/L (Figure 4-10). On average, the model predicted 38% NH_4^+ -N removal in the north plant raceway compared to 52% based on the observed data. With respect to NO_3^- -N, the model predicted an average effluent concentration of 3.0 mg/L compared to the average observed effluent concentration of 5.3 mg/L (Figure 4-11). The average model removal of NO_3^- -N was 82% compared to the average observed of 67%.

The NH_4^+ -N concentration on 14 January 2012 was high. The observed sand filter NH_4^+ -N concentration was five times greater than the solids tank on that sample day (Boxman, 2013).

Like the solids tank, the model was unable to produce the high $\text{NH}_4^+\text{-N}$ concentrations observed in the sand filter. The sand filter was not modeled for physical, biological and chemical processes, creating lower model $\text{NH}_4^+\text{-N}$ concentrations than what was observed.

The $\text{NO}_3^-\text{-N}$ concentration on 17 May 2011 in the north plant raceway was also high. The observed sand filter $\text{NO}_3^-\text{-N}$ concentration was three times lower than the north plant raceway (Boxman, 2013). Similar to the south plant raceway on that same sample day, plant trays could have been moved and sediments removed from underneath the plant trays, creating an environment not suitable for denitrification.

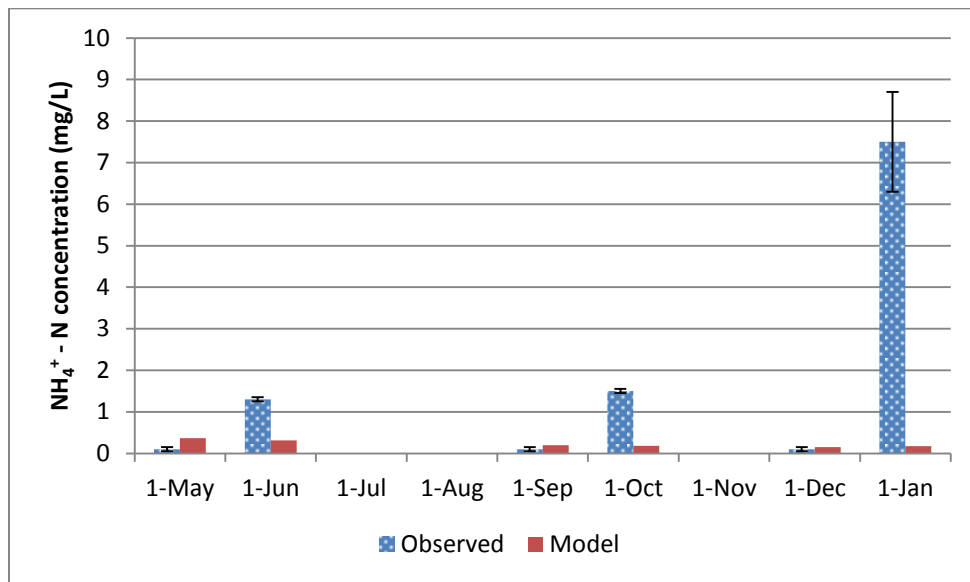


Figure 4-10. Effluent $\text{NH}_4^+\text{-N}$ concentration from the north plant raceway (W3).

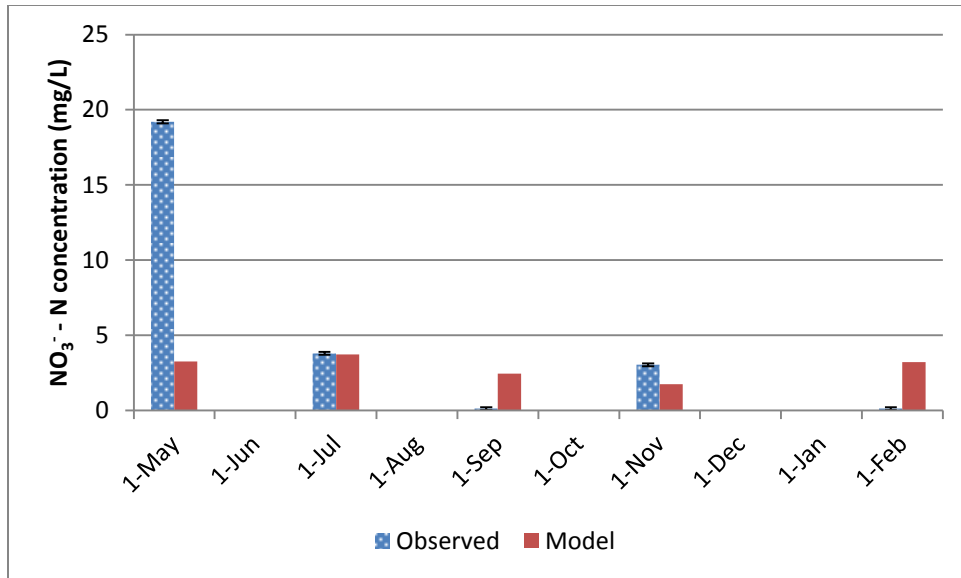


Figure 4-11. Effluent NO_3^- -N concentration from the north plant raceway (W3).

4.7 Fate of Nitrogen

From the model, the sand filter-north plant raceway combo removed the most nitrogen of the three solid treatment processes (Figure 4-12). Denitrification was the major nitrogen removal process in the south and north plant raceways, accounting for 59.0% and 54.6% of the nitrogen removal respectively (Figure 4-13). This was most likely due to the fact that NO_3^- -N was the form of nitrogen present at the highest concentration in the system and that DO and bioavailable COD concentrations provided favorable conditions for denitrifying bacteria. Plant and soil uptake represented only 0.20% in both plant raceways and sedimentation only 0.1%. Of the nitrogen remaining in both plant raceways, NO_3^- -N was the largest and NH_4^+ -N was the smallest.

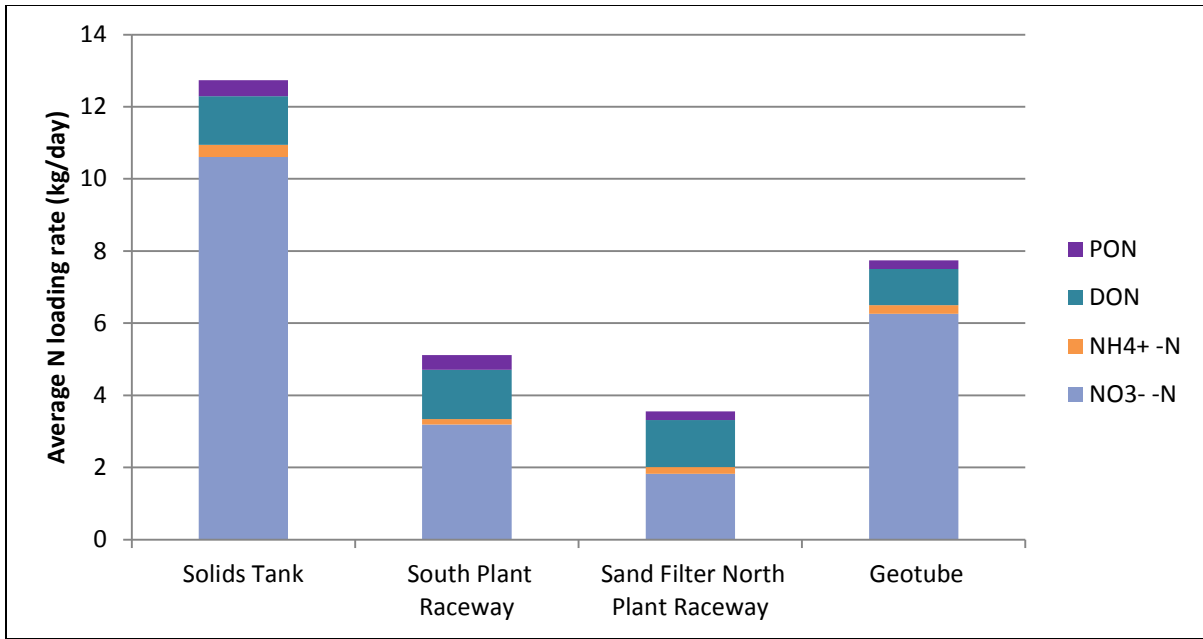


Figure 4-12. Comparison between the solids tank, south plant raceway, sand filter and north plant raceway combo and the geotube with respect to the four different nitrogen species.

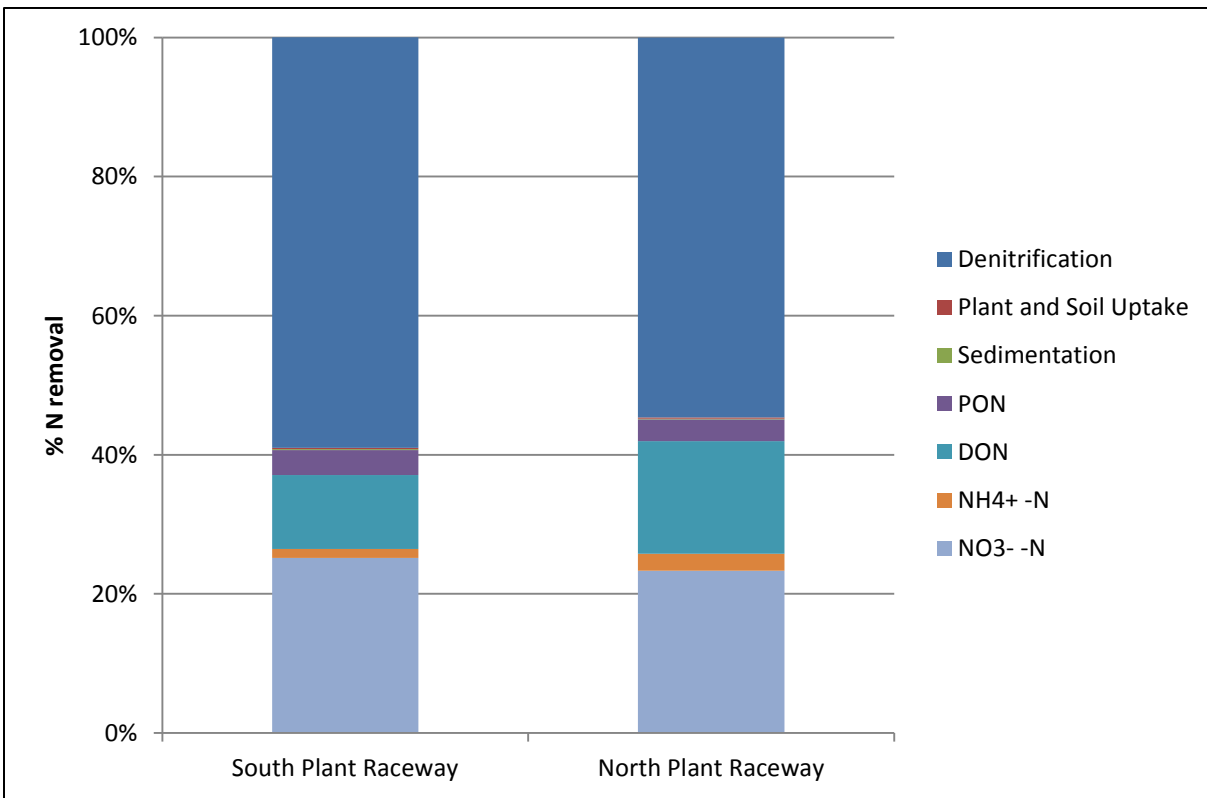


Figure 4-13. Fate of nitrogen comparing the south and north plant raceway.

Only a few studies have been performed on the nitrogen mass balance involving constructed wetlands (Kadlec and Wallace, 2009). In Orlando, Florida, a free water surface constructed wetland was used to polish treated municipal wastewater (Kadlec and Wallace, 2009). It was estimated that 52% of the nitrogen was removed by gasification, 30% remained in the effluent and 18% was stored as either biomass or sediments. The authors used the term gasification to describe all nitrogen transformation processes that turn nitrogen into a gas form, including denitrification, volatilization and anammox. In Tanazania, Australia, a horizontal subsurface flow wetland was constructed to treat a primary facultative pond effluent located at a university (Kadlec and Wallace, 2009). It was estimated that gasification accounted for 48.8% of the nitrogen while 46.4% remained in the effluent and 4.8% was stored in the system (Kadlec and Wallace, 2009). The Mote IAS model showed that 41% and 45% of the nitrogen remained in the water from the south and north plant raceways, respectively. This is similar to the Orlando and Tanazania constructed wetlands. However, the Mote IAS model had a higher percentage of denitrification than the Orlando and Tanazania constructed wetlands at 59% and 55% while the plant and soil accumulation was much lower at 0.3%.

Kadlec and Wallace (2009) describe nitrification as the main transformation for $\text{NH}_4^+\text{-N}$ in constructed wetlands. Nitrification represented 60% of the south plant raceway transformations and 71% of the north plant raceway. Hydrolysis was larger in the south plant raceway than the north as expected. The north plant raceway had a sand filter where most of the hydrolysis would occur as PON is captured.

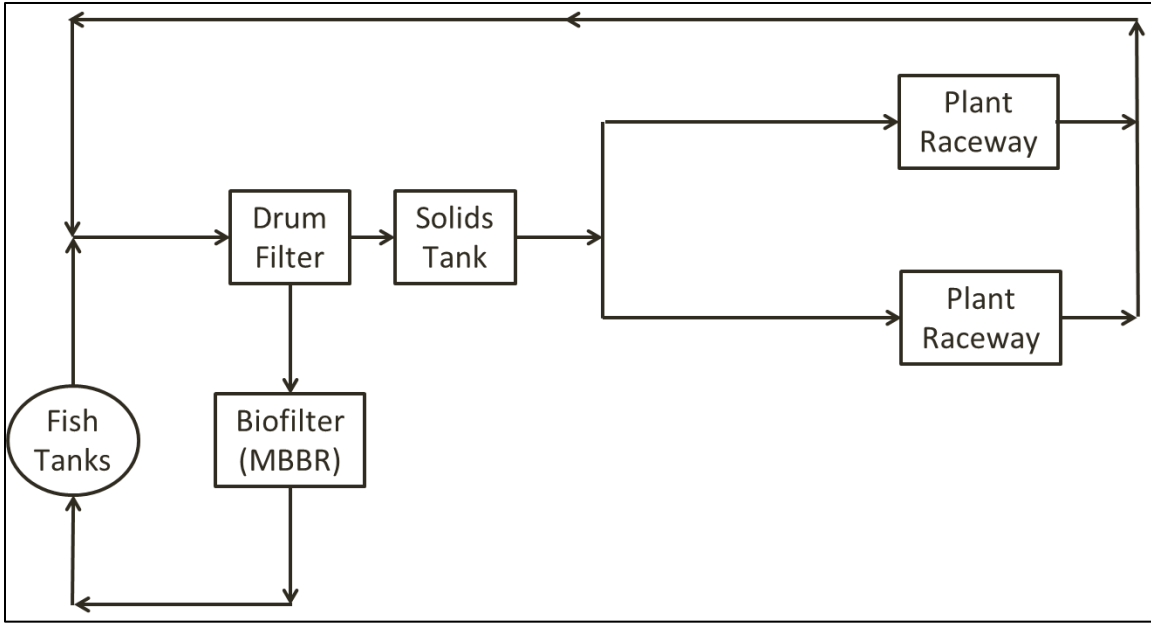


Figure 4-15. Option two if the Mote IAS was redesigned where the flow from the solids tank was divided to two plant raceways before flowing back to the drum filter.

In option one, the geotube would act as the initial treatment process while the plant raceway would act as a polishing step. The overall TN removal from the geotube and south plant raceway combined was 74% compared with 57% under the original system. The nitrogen removal processes for option one is shown in Figure 4-16. The option one geotube maintained an average TN removal of 37% compared to 38% under the original system. Denitrification is still the main removal mechanism in the plant raceway, followed by plants and sedimentation. In option two, the two plant raceways are the only treatment processes for the solids tank. The nitrogen removal processes for option two is in Figure 4-17. Under this option, the overall TN removal was 60%, similar to the original system's removal of 57%. Again, denitrification is the main nitrogen removal mechanism with plants, soil and sedimentation contributed very little to the removal process.

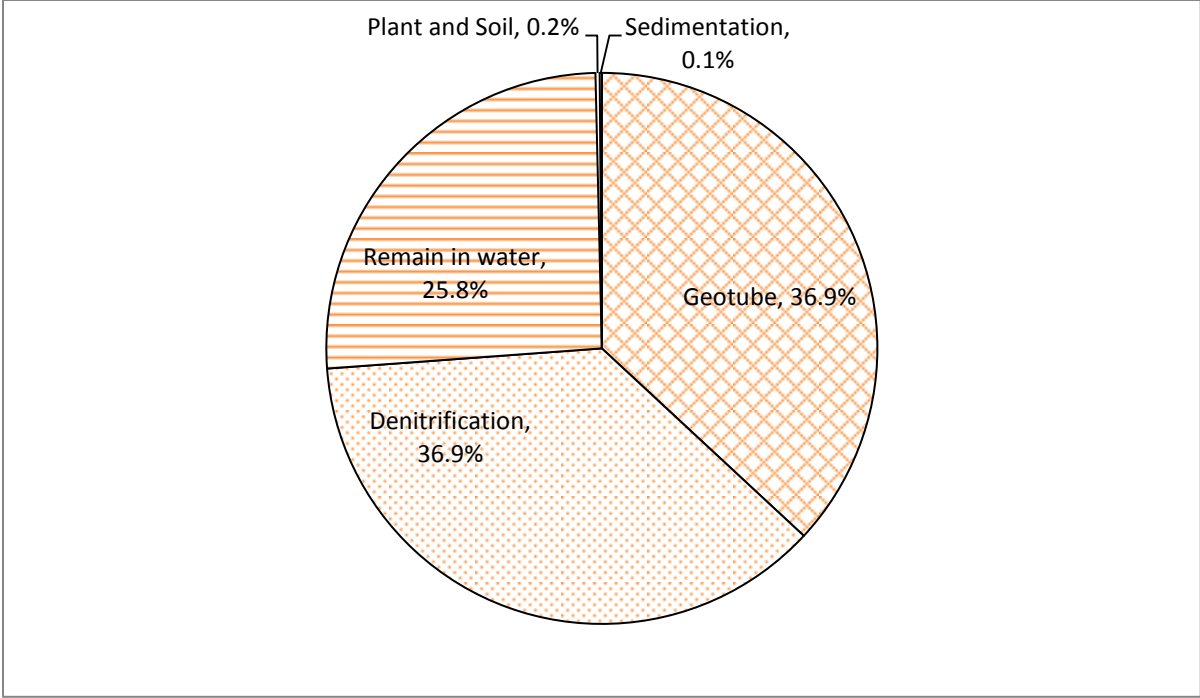


Figure 4-16. The nitrogen removal processes if option one is implemented.

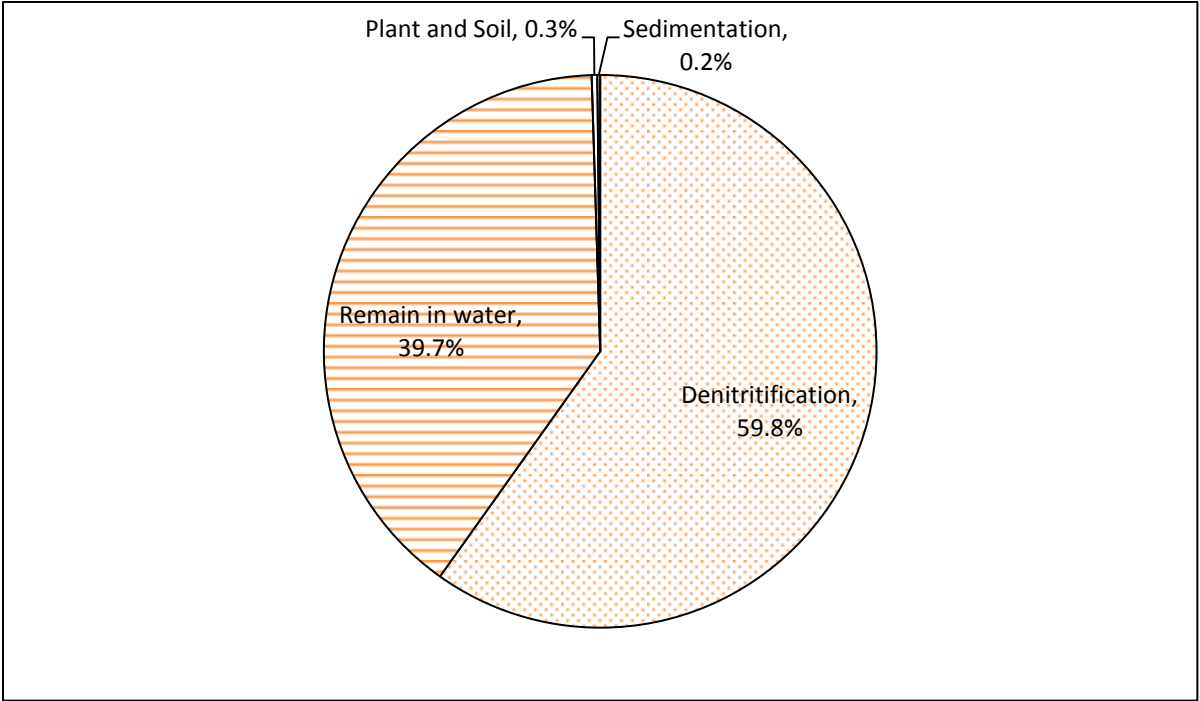


Figure 4-17. The nitrogen removal process if option two is implemented.

If a commercial developer wanted to duplicate the Mote IAS, option two would be the best choice. Although option one has a higher removal efficiency, it would also have a higher cost due to the purchase and maintenance of a geotube. The original system would be less effective and would also require the geotube. Option two requires no geotube and increases the amount of plant production compared to option one. Even though there is little difference between the removal efficiencies of option two and the original system, the overall cost of option two would be lower with no geotube.

CHAPTER 5: CONCLUSION

An IAS is a potential solution for some of the environmental impacts associated with aquaculture. By incorporating an agriculture component to aquaculture, the solids waste can be used as a fertilizer for producing a plant crop. The Mote IAS produced market size Florida pompano and various plants for wetland restoration while at the same time effectively treating the recirculating water. By including an agriculture component, the overall profitability for the system increases.

The first objective of this study was to develop, calibrate and evaluate a marine IAS model of the fate of nitrogen in the Mote IAS. A conceptual model was constructed by examining the nitrogen cycle and determining which processes applied to each stage of the system. The MBBR and south and north plant raceways were modeled using physical, biological and chemical processes while the solids tank, sand filter and geotube were not. It was not feasible to obtain internal samples of the sand filter and geotube to determine what processes were occurring inside. The model calibration involved experimental, literature and calibrated parameters. Using the sum of the squared residuals, the model was calibrated by adjusting the parameters until the model's output was a best fit to the observed data. A sensitivity analysis was performed and also used the sum of the squared residuals to determine which parameters caused large variations in the model output. Of all the parameters, the denitrifier constant (k_2) caused the most variation in the model output. The denitrifier constant involved the maximum

specific growth rate, yield coefficient and half saturation constant for denitrifiers. The denitrifier fraction of VSS was another parameter that the model output was sensitive to. The model was not sensitive to the plant uptake preference factors because of the minor role plants have in nitrogen removal. Overall, the model predicted within one standard deviation of the observed mean for all physical stages except for the sand filter.

Of the nitrogen removal processes in the plant raceways, denitrification was the largest, accounting for 59% and 55% in the south and north plant raceways respectively. About 41% to 45% of the nitrogen remained in the water, similar to other nitrogen mass balances involving constructed wetlands. Of the $\text{NH}_4^+\text{-N}$ processes, nitrification was the largest, accounting for 64% and 71% in the south and north plant raceways respectively.

The last objective was to determine other treatment designs if the Mote IAS was redesigned. Two options were explored. The first option contained a geotube and one plant raceway in series as the treatment system while the second option explored using two plant raceways in parallel without a geotube. The first option had a better overall removal efficiency compared to the second, but would cost more with the geotube. The second option would also produce more plants since it had twice the area for plant growth.

Further research should be involved in the investigation of the solids tank, sand filter and geotube. Those stages were not modeled for their physical, chemical and biological processes. Additional, further research should investigate the microbial parameters such as the maximum specific growth rates or the half saturation constants used in constructed wetlands.

REFERENCES

- Aquatic Plants of Florida. (2012). "Plant Inventory: Salt Tolerant Plants." Aquatic Plants of Florida. <http://apofl.com/plants/plant-inventory/salt-tolerant-plants/page/4/>. Retrieved on 20 September 2012.
- Berkman, H. (1995). "Central database." In *Thirteenth Annual Technical Report*; B. Goetze, D. Burke, M. McNamara and D. Clair (Eds); PD/A CRSP: Corvallis, OR.
- Boxman, S. (2013). "Evaluation of a pilot land based marine integrated aquaculture system." *Graduate School Theses and Dissertations*.
- Chen S. and Fornshell, G.C.G. (2000). "Effluents: dissolved compounds." In *Encyclopedia of Aquaculture*; R.R. Stickney (Ed.); John Wiley and Sons Inc: New York, NY.
- Craig, S.R. (2000). "Pompano Culture." In *Encyclopedia of Aquaculture*; R.R. Stickney (Ed.); John Wiley and Sons Inc: New York, NY.
- Di Toro, D.M., O'Connor, D.J. and Thomann, R.V. (1971). "A dynamic model of the phytoplankton population in the Sacramento-San Joaquin Delta." *Advances in Chemistry Series/ American Chemical Society*, 106, 131-180
- Downing, A.L. (1966). "Population dynamics in biological systems." *3rd International Water Policy Research*, WPCF, Munich, Germany, 117-137.
- Eaton, A.D., Franson, M.A.H., American Public Health Association, American Water Works Association and Water Environment Federation. (2005). *Standard methods for the examination of water and wastewater: centennial edition*. American Public Health Association: Washington DC
- Elmore, H.L. and Hayes, T.W. (1960). "Solubility of atmospheric oxygen in water." *Journal of the Sanitary Engineering Division*, 86, 41-53.

- Ernst, D.H. (2000). "Performance engineering." In *Encyclopedia of Aquaculture*; R.R. Stickney (Ed.); John Wiley and Sons Inc: New York, NY.
- Eweis, J.B., Ergas, S.J., Chang, D.P.Y. and Schroeder, E.D. (1998). *Bioremediation principles*. McGraw Hill, Boston, MA.
- FAO (2001). "Integrated Agriculture-Aquaculture." *Food and Agriculture Organization of the United Nations*. <http://www.fao.org/docrep/005/Y1187E/y1187e03.htm#c>. Retrieved on 2 September 2012.
- FAO. (2008). "The State of World Fisheries and Aquaculture." *Food and Agriculture Organization of the United Nations*: Rome, Italy.
- FAO. (2012). "The State of World Fisheries and Aquaculture." *Food and Agriculture Organization of the United Nations*: Rome, Italy.
- Florida Department of Environmental Protection. (2012). "What are Mangroves?" Florida DEP. <http://www.dep.state.fl.us/coastal/habitats/mangroves.htm>. Retrieved on 25 September 2012.
- Hem, L.J., Rusten, B. and Odegaard H. (1993). "Nitrification in a moving bed biofilm reactor." *Water Resources*, 28, 6, 1425-1433.
- Henze, M. and Mladenovski, C. (1991). "Hydrolysis of particulate substrate by activated sludge under aerobic, anoxic and anaerobic conditions." *Water Research*, 25, 1, 61-64.
- ISEE. (2013). "STELLA, systems thinking for education and research." *ISEE*. <http://www.iseesystems.com/software/Education/StellaSoftware.aspx>. Retrieved on 15 June 2013.
- Jamu, D.M. and Piedrahita, R.H. (2002a). "An organic matter and nitrogen dynamics model for the ecological analysis of integrated aquaculture/agriculture systems. I. model development and calibration." *Environmental Modelling and Software*, 17, 571-582.
- Jamu, D.M. and Piedrahita, R.H. (2002b). "An organic matter and nitrogen dynamics model for the ecological analysis of integrated aquaculture/agriculture systems. II. model evaluation and application." *Environmental Modelling and Software*, 17, 583-592.
- Kadlec, R.H. and Wallace, S.D. (2009). *Treatment wetlands*. CRC Press, Boca Raton, FL.

Kruglick, A. W. (2012). "Water quality monitoring in a pilot marine integrated aquaculture system." *Graduate School Theses and Dissertations*.

Losordo T.M. and Hobbs, A.O. (2000). "Using computer spreadsheets for water flow and biofilter sizing in recirculating aquaculture production systems." *Aquacultural Engineering*, 23, 95-102.

Mayo, A.W. and Mutamba, J. (2005). "Modelling nitrogen removal in a coupled HRP and unplanted horizontal flow subsurface gravel bed constructed wetland." *Physics and Chemistry of the Earth*, 30, 673-679.

Murphy, M.D., Muller, R.G. and Guindon, K. (2008). "A stock assessment for pompano, *Trachinotus carolinus*, in Florida waters through 2005." Florida Fish and Wildlife Conservation Commission.

Nath, S. (1996). "Development of a decision support system for pond aquaculture. *Ph.D. dissertation, Oregon State University*.

NRCS. (2007). "Manure chemistry: nitrogen, phosphorus and carbon." *Natural Resources Conservation Service*.

http://www.or.nrcs.usda.gov/technical/engineering/environmental_engineering/Compost_Netmeting/Manure_Chemistry_Info_Sheet.pdf. Retrieved on 10 June 2013.

Ouyang, Y. (2008). "Modeling the mechanisms for uptake and translocation of dioxane in a soil-plant ecosystem with STELLA." *Journal of Contaminant Hydrology*, 95, 17-29.

Piedrahita, R.H. (1990). "Calibration and validation of TAP, an aquaculture pond water quality model." *Aquacultural Engineering*, 9, 75-96.

Randall, D.J. and Tsui, T.K.N. (2002). "Ammonia toxicity in fish." *Marine pollution bulletin*, 45, 17-23.

Rittman B.E. and McCarty, P.L. (2001). *Environmental biotechnology: principles and applications*. McGraw Hill, New York, New York.

Rusten, B., Eikebrokk, B., Ulgenes, Y. and Lygren, E. (2006). "Design and operations of the Kaldnes moving bed biofilm reactors." *Aquacultural Engineering*, 34, 322-331.

Schlesinger, W.H. (1997). *Biogeochemistry: an analysis of global change*. Academic Press, San Diego, California.

Schulz, C., Gelbrecht, J. and Rennert, B. (2003). "Treatment of rainbow trout farm effluents in constructed wetland with emergent plants and subsurface horizontal water flow." *Aquaculture*, 217, 207-221.

Spitters, C.J.T., van Keulen, H., and van Kraalingen, D.W.G. (1989). "A simple and universal crop growth model: SUCROS1. In *simulation and systems management in crop protection*;

Rabbinge, S., Ward, S.A. and van Laar, H.H. (Eds.); Simulation Monographs: Pudoc, Wageningen.

Timmons M.B., and Ebling, J.M., Wheaton, F.W., Summerfelt, S.T. and Vinci, B.J. (2002). *Recirculating aquaculture systems, 2nd Ed.* Cayuga Aqua Ventures, New York, New York.

Treece, G.D. (2000). "Pollution." In *Encyclopedia of aquaculture*; R.R. Stickney (Ed.); John Wiley and Sons Inc: New York, NY.

Tucker, C.S., Hargreaves, J.A. and Boyd, C.E. (2008). "Better management practices for freshwater pond aquaculture." In *Environmental Best Management Practices for Aquaculture*; C.S. Tucker and J.A. Hargreaves (Eds.); Wiley Blackwell: Oxford, UK.

US EPA. (1993). *Manual: nitrogen control.* US EPA, Washington D.C.

US EPA. (2000). *Manual: Constructed Wetlands Treatment of Municipal Wastewater.* US EPA, Washington D.C.

Vaccari, D.A., Strom, P.F. and Alleman, J.E. (2006). *Environmental biology for engineers and scientists.* John Wiley & Sons, Hoboken, New Jersey.

Weirich, C.R. (2011). "An overview of US pompano research and culture efforts to date." *Aquaculture America 2011 Conference.*

<https://www.was.org/WASMeetings/Meetings/ShowAbstract.aspx?Id=21429>. Retrieved on 12 September 2012.

Weirich, C.R., Wills, P.S., Baptiste, R.M., Woodward, P.N. and Riche, M.A. (2009). "Production characteristics and body composition of Florida pompano reared to market size at two different densities in low salinity recirculating aquaculture systems." *North American Journal of Aquaculture*, 71, 165-173.

Wik, T.E.I., Linden, B.T. and Wramner, P.I. (2009). "Integrated dynamic aquaculture and wastewater treatment modeling for recirculating aquaculture systems." *Aquaculture*, 287, 361-370.

APPENDICES

Appendix A – List of Symbols

θ	Arrhenius constant (unitless)
β	Biofilm constant involving the NH_4^+ -N diffusion constant, the length of the biofilm and the reaction rate (unitless)
a	Surface area per volume of the media in the MBBR (m^2/m^3)
C_{1A}	NH_4^+ -N concentration in the solids tank (mg/L)
C_{1D}	DON concentration in the solids tank (mg/L)
C_{1N}	NO_3^- -N concentration in the solids tank (mg/L)
C_{1P}	PON concentration in the solids tank (mg/L)
C_{2A}	NH_4^+ -N concentration in the south plant raceway (mg/L)
C_{2D}	DON concentration in the south plant raceway (mg/L)
C_{2N}	NO_3^- -N concentration in the south plant raceway (mg/L)
C_{2P}	PON concentration in the south plant raceway (mg/L)
C_{3A}	NH_4^+ -N concentration in the north plant raceway (mg/L)
C_{3D}	DON concentration in the north plant raceway (mg/L)
C_{3N}	NO_3^- -N concentration in the north plant raceway (mg/L)
C_{3P}	PON concentration in the north plant raceway (mg/L)
C_{4A}	NH_4^+ -N concentration in the geotube (mg/L)
C_{4D}	DON concentration in the geotube (mg/L)
C_{4N}	NO_3^- -N concentration in the geotube (mg/L)
C_{4P}	PON concentration in the geotube (mg/L)
C_{5A}	NH_4^+ -N concentration in the sand filter (mg/L)
C_{5D}	DON concentration in the sand filter (mg/L)
C_{5N}	NO_3^- -N concentration in the sand filter (mg/L)

Appendix A (Continued)

C _{5P}	PON concentration in the sand filter (mg/L)
C _{6A}	Liquid phase NH ₄ ⁺ -N concentration in the MBBR (mg/L)
C _{7A}	NH ₄ ⁺ -N concentration in the MBBR (mg/L)
C _{7D}	DON concentration in the MBBR (mg/L)
C _{7N}	NO ₃ ⁻ -N concentration in the MBBR (mg/L)
C _{7P}	PON concentration in the MBBR (mg/L)
C _{8A}	NH ₄ ⁺ -N concentration in the fish tanks (mg/L)
C _{8D}	DON concentration in the fish tanks (mg/L)
C _{8N}	NO ₃ ⁻ -N concentration in the fish tanks (mg/L)
C _{8P}	PON concentration in the fish tanks (mg/L)
C _{9A}	NH ₄ ⁺ -N concentration in the drum filter (mg/L)
C _{9D}	DON concentration in the drum filter (mg/L)
C _{9N}	NO ₃ ⁻ -N concentration in the drum filter (mg/L)
C _{9P}	PON concentration in the drum filter (mg/L)
C _{10A}	NH ₄ ⁺ -N concentration in the solids tank (mg/L)
C _{10D}	DON concentration in the solids tank (mg/L)
C _{10N}	NO ₃ ⁻ -N concentration in the solids tank (mg/L)
C _{10P}	PON concentration in the solids tank (mg/L)
C _{COD}	COD concentration in the plant raceway (mg/L)
C _{DO}	DO concentration in the plant raceway (mg/L)
C _{salt}	Concentration of salt in the plant raceway (mg/L)
D	Day (day)

Appendix A (Continued)

f_{4A}	Fraction of the NH_4^+ -N removed by the geotube
f_{4D}	Fraction of the DON removed by the geotube
f_{4N}	Fraction of the NO_3^- -N removed by the geotube
f_{4P}	Fraction of the PON removed by the geotube
f_{5P}	Fraction of the PON removed by the sand filter
f_{5N}	Fraction of the NO_3^- -N removed by the sand filter
f_{10A}	Fraction of the drum filter's NH_4^+ -N entering the MBBR
f_{10D}	Fraction of the drum filter's DON entering the MBBR
f_{10N}	Fraction of the drum filter's NO_3^- -N entering the MBBR
f_{10P}	Fraction of the drum filter's PON entering the MBBR
f_A	Fraction of feed in the fish tank converted to NH_4^+ -N
f_{acc}	Fraction of PON in the plant soil
f_D	Fraction of feed in the fish tank converted to DON
f_{de}	Fraction of NO_3^- -N that was denitrified in the solids tank
f_{ni}	Fraction of NH_4^+ -N nitrified in the fish tank
f_P	Fraction of feed in the fish tank converted to PON
f_{sed}	Fraction of PON found in the sediments
f_{up}	Fraction of TN concentration take up by plants in the plant raceway
L_B	Thickness of the biofilm in the MBBR (m)
k_{MBni}	First order nitrification rate coefficient in the MBBR (1/day)
k_{mi}	First order rate for ammonification (1/day)
k_{ni}	First order nitrification rate in the plant raceway (1/day)

Appendix A (Continued)

k_{hyd}	First order rate for hydrolysis (1/day)
K_{COD}	Half saturation constant for COD (mg/L)
K_{de}	Half saturation constant for denitrifiers (mg/L)
K_{DO}	Half saturation constant for DO (mg/L)
K_{ni}	Half saturation constant for nitrifiers (mg/L)
N	Liquid phase NH_4^+ -N flux to the biofilm ($\text{mg}/\text{m}^2 \cdot \text{day}$)
P_1	Preference factor of plant uptake for NH_4^+ -N
P_2	Preference factor of plant uptake for NO_3^- -N
Q_1	Flow through the solids tank (L/day)
Q_2	Flow through the south plant raceway, north plant raceway or geotube (L/day)
Q_7	Flow through the MBBR or fish tanks (L/day)
Q_{10}	Flow through the drum filter (L/day)
r_{acc}	Rate of PON accumulation in the soil of the plant raceway ($\text{mg}/\text{L} \cdot \text{day}$)
r_{de}	Rate of denitrification in the plant raceway ($\text{mg}/\text{L} \cdot \text{day}$)
r_{feed}	Rate of feed added to the fish tanks ($\text{mg}/\text{L} \cdot \text{day}$)
r_{hyd}	Rate of hydrolysis ($\text{mg}/\text{L} \cdot \text{day}$)
r_{MBni}	Rate of nitrification in the MBBR ($\text{mg}/\text{L} \cdot \text{day}$)
r_{mi}	Rate of mineralization ($\text{mg}/\text{L} \cdot \text{day}$)
r_{ni}	Rate of nitrification in the plant raceway ($\text{mg}/\text{L} \cdot \text{day}$)
r_{sed}	Rate of PON sedimentation ($\text{mg}/\text{L} \cdot \text{day}$)
r_{up1}	Rate of plant uptake of NH_4^+ -N ($\text{mg}/\text{L} \cdot \text{day}$)
r_{up2}	Rate of plant uptake of NO_3^- -N ($\text{mg}/\text{L} \cdot \text{day}$)

Appendix A (Continued)

T	Water temperature ($^{\circ}\text{C}$)
T_0	Average water temperature of the plant raceway ($^{\circ}\text{C}$)
T_A	Amplitude of sine wave ($^{\circ}\text{C}$)
T_P	Period of sine wave (day)
\hat{u}_{de}	Max specific growth rate for denitrifiers (1/day)
\hat{u}_{ni}	Max specific growth rate for nitrifiers (1/day)
V_{FT}	Volume of the fish tanks (L)
V_{GE}	Volume of the geotube (L)
V_{MB}	Volume of the MBBR (L)
V_{PR}	Volume of the plant raceway (L)
V_{SF}	Volume of the sand filter (L)
V_{ST}	Volume of the solids tanks (L)
X_{de}	Active biomass for denitrifiers (mg/L)
X_{ni}	Active biomass for nitrifiers (mg/L)
Y_{de}	Yield coefficient for denitrifiers (g biomass/g NO_3^- -N)
Y_{ni}	Yield coefficient for nitrifiers (g biomass/g NH_4^+ -N)

Appendix B – List of Assumptions

The following is a list of assumptions for each physical stage of the Mote IAS. A more detailed description of each stage can be found in Chapter 3.

B.1 Fish Tank

1. Nitrogen in feed is only in the protein.
2. Nitrogen concentration from fish excretion was constant due to feeding schedule.
3. Of the 100% of the nitrogen in feed, 30% was retained as fish biomass, 14% was wasted as PON, 5.6% was wasted as DON and 50.4% was wasted as NH_4^+ (see Figure 3-4).
4. PON excreted by fish is rapidly hydrolyzed to DON.
5. 10% of NH_4^+ -N is nitrified due to the aerobic conditions and presence of nitrifying bacteria attached to the tank surfaces.

B.2 Drum Filter

1. Nitrogen is only transported, not transformed.

B.3 Solids Tank

1. Outflow is equally divided between the south and north plant raceways and the geotube.
2. The only processes occurring are ammonification and denitrification.
3. 15% of NO_3^- -N is denitrified due to the low DO concentrations.

Appendix B (Continued)

B.4 MBBR

1. The MBBR behaves like a completely mixed flow reactor.
2. Nitrification is the only transformation process

B.5 South and North Plant Raceways

1. The plant raceways behaves like a constructed wetland and a completely mixed flow reactor.
2. All processes operate under first order reaction rates.
3. Plants uptake NH_4^+ -N and NO_3^- -N.
4. VSS concentration was a function of the feed.
5. Nitrifiers and denitrifiers were a function of the VSS concentration.

B.6 Sand Filter

1. Ammonification was the only transformation process occurring.

Appendix C –Equations Checked in Microsoft Excel

Prior to implementation in STELLA™, the equations used to describe the physical, chemical and biological processes occurring in the plant raceways and the MBBR were compared to the observed data by using Microsoft Excel. Since the both plant raceways utilized the same equations, only the observed data from the south plant raceway was checked. The influent data used for the south plant raceway model was from the solids tank (W1) and the model output was compared against the observed effluent concentration from the south plant raceway (W2). The model $\text{NH}_4^+\text{-N}$ concentration remained below 1.25 mg/L while the observed data remained below 2.5 mg/L (Figure C-1). The model $\text{NO}_3^-\text{-N}$ concentration followed the same trends as the observed $\text{NO}_3^-\text{-N}$ concentration, climbing for the first two data sets and then remaining below 2 mg/L for the rest (Figure C-2).

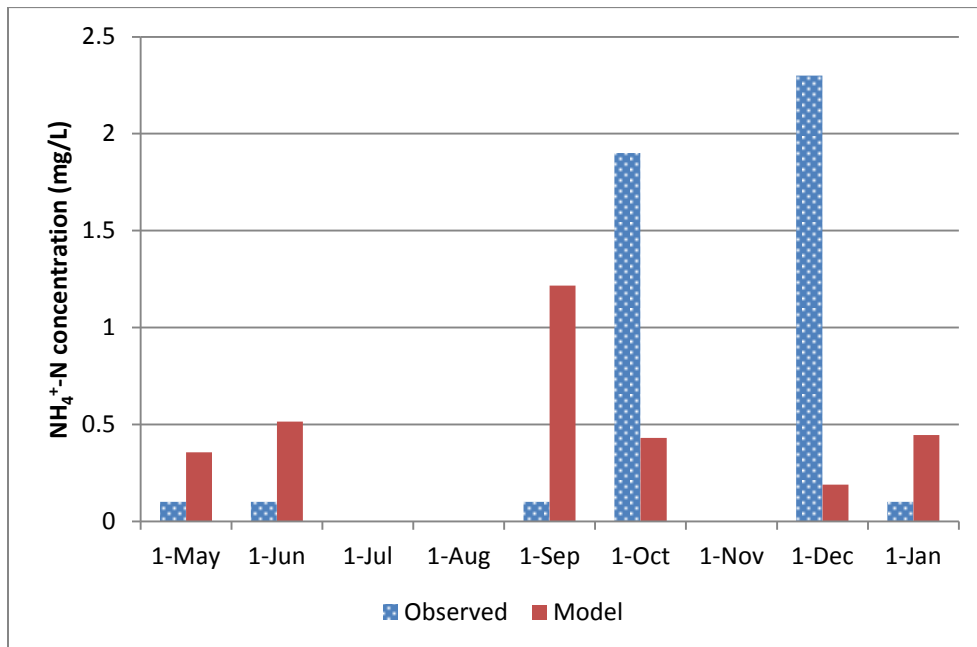


Figure C-1. Equation check of the $\text{NH}_4^+\text{-N}$ concentration in the south plant raceway (W2) in Microsoft Excel.

Appendix C (Continued)

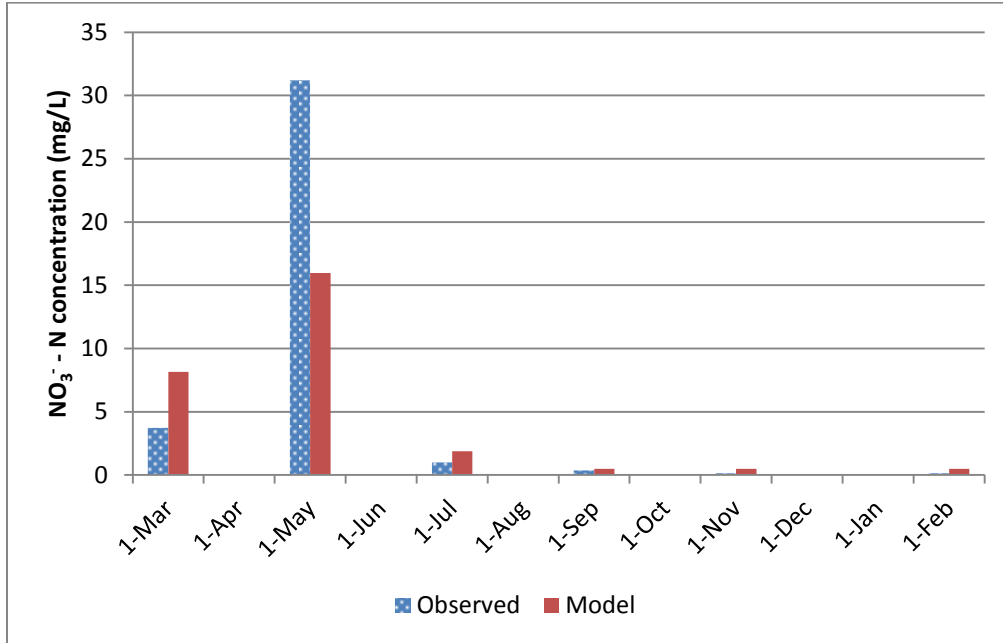


Figure C-2. Equation check of the NO_3^- -N concentration in the south plant raceway (W2) in Microsoft Excel.

The observed data from the drum filter (W6) was used as the influent for the model's MBBR. The effluent from the model was compared to the observed effluent (W7). The average observed effluent NH_4^+ -N concentration was 0.11 mg/L while the average model effluent was 0.10 mg/L (Figure C-3). With respect to NO_3^- -N, the model output and the observed data were roughly the same (Figure C-4).

Appendix C (Continued)

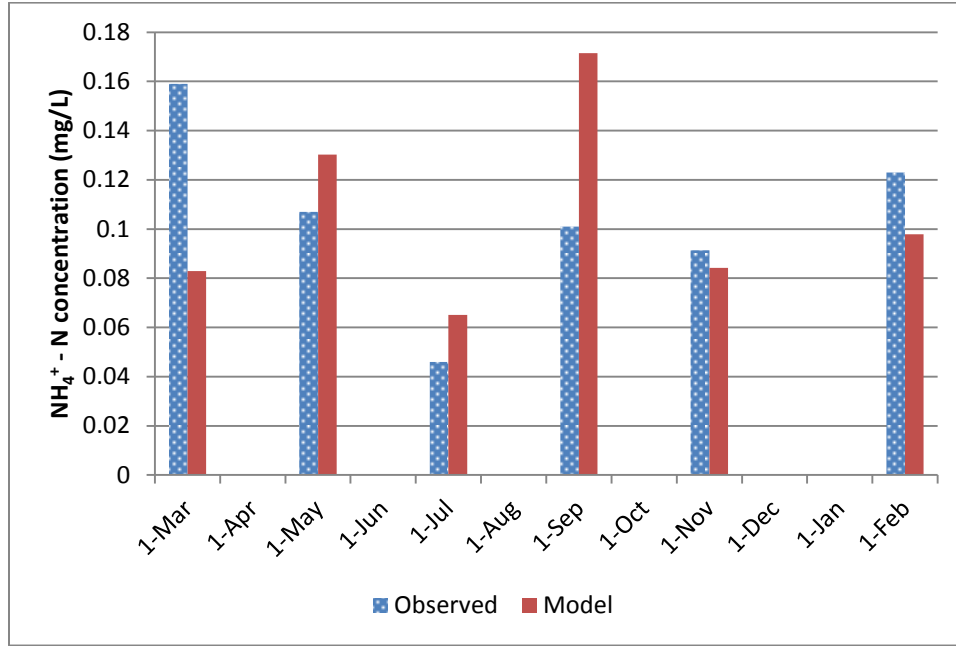


Figure C-3. Equation check of the NH_4^+ -N concentration in the MBBR in Microsoft Excel.

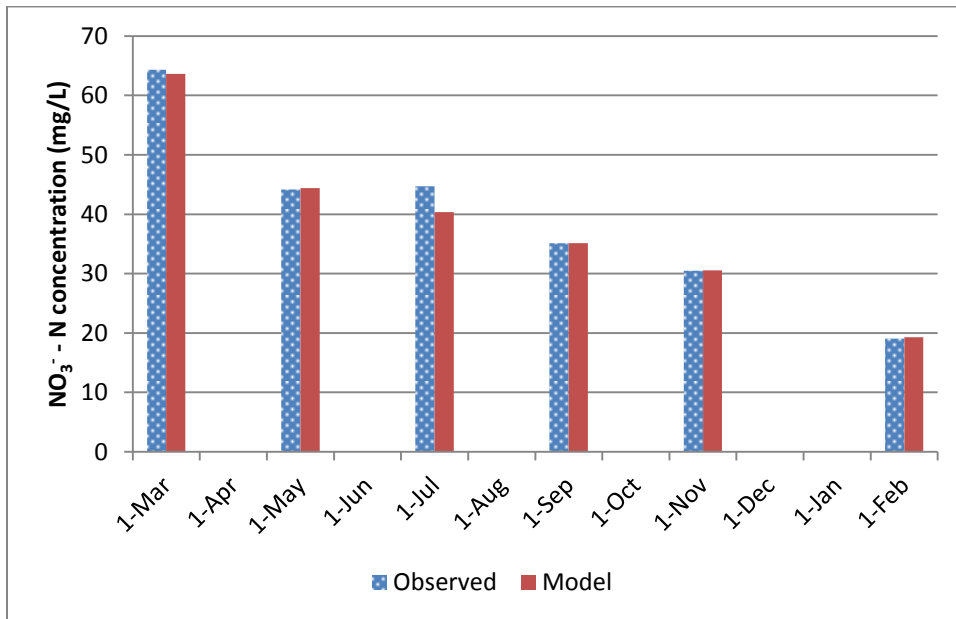


Figure C-4. Equation check of the NO_3^- -N concentration of the MBBR in Microsoft Excel.

Appendix D – Stella™ Equations

$DO_plant_beds(t) = DO_plant_beds(t - dt) + (DO_in - DO_out) * dt$

INIT $DO_plant_beds = 0$

INFLOWS:

$DO_in = DO_Sat - (0.995/0.2) * DO_salt_factor$

OUTFLOWS:

$DO_out = DO_plant_beds$

$Drum_filter_DON(t) = Drum_filter_DON(t - dt) + (Drum_filter_DON_in - Drum_filter_DON_out) * dt$

INIT $Drum_filter_DON = 0$

INFLOWS:

$Drum_filter_DON_in =$

$(DON_in_fish_tank) + (Geotube_DON_out) + (South_plant_DON_out) + (North_plant_DON_out)$

OUTFLOWS:

$Drum_filter_DON_out = Drum_filter_DON$

$Drum_filter_NH4(t) = Drum_filter_NH4(t - dt) + (Drum_filter_NH4_in - Drum_filter_NH4_out) * dt$

INIT $Drum_filter_NH4 = 0$

INFLOWS:

$Drum_filter_NH4_in =$

$(NH4_in_fish_tank) + (Geotube_NH4_out) + (South_plant_NH4_out) + (North_plant_NH4_out)$

OUTFLOWS:

$Drum_filter_NH4_out = Drum_filter_NH4$

$Drum_filter_NO3(t) = Drum_filter_NO3(t - dt) + (Drum_filter_NO3_in - Drum_filter_NO3_out) * dt$

INIT $Drum_filter_NO3 = 0$

INFLOWS:

$Drum_filter_NO3_in =$

$(NO3_in_fish_tank) + (Geotube_NO3_out) + (South_plant_NO3_out) + (North_plant_NO3_out)$

OUTFLOWS:

$Drum_filter_NO3_out = Drum_filter_NO3$

$Drum_filter_PON(t) = Drum_filter_PON(t - dt) + (Drum_filter_PON_in - Drum_filter_PON_out) * dt$

INIT $Drum_filter_PON = 0$

INFLOWS:

$Drum_filter_PON_in = (PON_in_fish_tank) + (Geotube_PON_out)$

OUTFLOWS:

$Drum_filter_PON_out = Drum_filter_PON$

Appendix D (Continued)

$$\text{Feed}(t) = \text{Feed}(t - dt) + (\text{Feed_input} - \text{Feed_wasted} - \text{Feed_consumed}) * dt$$

$$\text{INIT Feed} = 0$$

INFLOWS:

$$\text{Feed_input} = \text{day_0_to_480}$$

OUTFLOWS:

$$\text{Feed_wasted} = \text{Feed} * \text{Percent_feed_wasted}$$

$$\text{Feed_consumed} = \text{Feed} * \text{Percent_feed_consumed}$$

$$\text{Geotube_DON}(t) = \text{Geotube_DON}(t - dt) + (\text{Geotube_DON_in} - \text{Geotube_DON_out} -$$

$$\text{Geotube_DON_removed}) * dt$$

$$\text{INIT Geotube_DON} = 282759$$

INFLOWS:

$$\text{Geotube_DON_in} = \text{Solids_tank_DON_out_2}$$

OUTFLOWS:

$$\text{Geotube_DON_out} = \text{Geotube_DON}$$

$$\text{Geotube_DON_removed} = \text{Geotube_DON} * \text{Geotube_DON_removal_eff}$$

$$\text{Geotube_NH4}(t) = \text{Geotube_NH4}(t - dt) + (\text{Geotube_NH4_in} - \text{Geotube_NH4_out} -$$

$$\text{Geotube_NH4_removed}) * dt$$

$$\text{INIT Geotube_NH4} = 319556$$

INFLOWS:

$$\text{Geotube_NH4_in} = \text{Solids_tank_NH4_out_2}$$

OUTFLOWS:

$$\text{Geotube_NH4_out} = \text{Geotube_NH4}$$

$$\text{Geotube_NH4_removed} = \text{Geotube_NH4} * \text{Geotube_NH4_removal_eff}$$

$$\text{Geotube_NO3}(t) = \text{Geotube_NO3}(t - dt) + (\text{Geotube_NO3_in} - \text{Geotube_NO3_out} -$$

$$\text{Geotube_NO3_removed}) * dt$$

$$\text{INIT Geotube_NO3} = 6400367$$

INFLOWS:

$$\text{Geotube_NO3_in} = \text{Solids_tank_NO3_out_2}$$

OUTFLOWS:

$$\text{Geotube_NO3_out} = \text{Geotube_NO3}$$

$$\text{Geotube_NO3_removed} = \text{Geotube_NO3} * \text{Geotube_NO3_removal_eff}$$

$$\text{Geotube_PON}(t) = \text{Geotube_PON}(t - dt) + (\text{Geotube_PON_in} - \text{Geotube_PON_out} -$$

$$\text{Geotube_PON_removed}) * dt$$

$$\text{INIT Geotube_PON} = 38558$$

INFLOWS:

$$\text{Geotube_PON_in} = \text{Solids_tank_PON_out_2}$$

OUTFLOWS:

$$\text{Geotube_PON_out} = \text{Geotube_PON}$$

$$\text{Geotube_PON_removed} = \text{Geotube_PON} * \text{Geotube_PON_removal_eff}$$

Appendix D (Continued)

$$\text{MBBR_DON}(t) = \text{MBBR_DON}(t - dt) + (\text{MBBR_DON_in} - \text{MBBR_DON_out}) * dt$$

$$\text{INIT MBBR_DON} = 10073825$$

INFLOWS:

$$\text{MBBR_DON_in} = \text{DF_to_MBBR_DON_in}$$

OUTFLOWS:

$$\text{MBBR_DON_out} = \text{MBBR_DON}$$

$$\text{MBBR_NH4}(t) = \text{MBBR_NH4}(t - dt) + (\text{MBBR_NH4_in} - \text{MBBR_NH4_out} - \text{MBBR_nitrification}) * dt$$

$$\text{INIT MBBR_NH4} = 361944$$

INFLOWS:

$$\text{MBBR_NH4_in} = \text{DF_to_MBBR_NH4_in}$$

OUTFLOWS:

$$\text{MBBR_NH4_out} = \text{MBBR_NH4}$$

$$\text{MBBR_nitrification} =$$

$$(\text{MBBR_first_order_reaction_constant} * \text{MBBR_NH4} * \text{MBBR_biofilm_length}) * \text{MBBR_media_surface_area_per_volume} * \text{MBBR_volume}$$

$$\text{MBBR_NO3}(t) = \text{MBBR_NO3}(t - dt) + (\text{MBBR_nitrification} + \text{MBBR_NO3_in} - \text{MBBR_NO3_out}) * dt$$

$$\text{INIT MBBR_NO3} = 106899710$$

INFLOWS:

$$\text{MBBR_nitrification} =$$

$$(\text{MBBR_first_order_reaction_constant} * \text{MBBR_NH4} * \text{MBBR_biofilm_length}) * \text{MBBR_media_surface_area_per_volume} * \text{MBBR_volume}$$

$$\text{MBBR_NO3_in} = \text{DF_to_MBBR_NO3_in}$$

OUTFLOWS:

$$\text{MBBR_NO3_out} = \text{MBBR_NO3}$$

$$\text{MBBR_PON}(t) = \text{MBBR_PON}(t - dt) + (\text{MBBR_PON_in} - \text{MBBR_PON_out}) * dt$$

$$\text{INIT MBBR_PON} = 1373703$$

INFLOWS:

$$\text{MBBR_PON_in} = \text{DF_to_MBBR_PON_in}$$

OUTFLOWS:

$$\text{MBBR_PON_out} = \text{MBBR_PON}$$

$$\text{North_plant_DON}(t) = \text{North_plant_DON}(t - dt) + (\text{North_plant_hydrolysis} + \text{North_plant_DON_in} - \text{North_plant_ammonification} - \text{North_plant_DON_out}) * dt$$

$$\text{INIT North_plant_DON} = 300321$$

INFLOWS:

$$\text{North_plant_hydrolysis} =$$

$$(\text{North_plant_rate_of_hydrolysis} * \text{North_plant_PON} * (\exp((-0.2) * (20 - \text{Temperature}))))$$

$$\text{North_plant_DON_in} = \text{Sand_filter_DON_out}$$

Appendix D (Continued)

OUTFLOWS:

$$\begin{aligned}\text{North_plant_ammonification} &= (0.002 * \text{Temperature}) * \text{North_plant_DON} \\ \text{North_plant_DON_out} &= \text{North_plant_DON}\end{aligned}$$

$$\begin{aligned}\text{North_plant_NH4}(t) &= \text{North_plant_NH4}(t - dt) + (\text{North_plant_ammonification} + \\ &\text{North_plant_NH4_in} - \text{North_plant_nitrification} - \text{North_plant_NH4_out} - \\ &\text{North_plant_NH4_plant_uptake}) * dt\end{aligned}$$

$$\text{INIT North_plant_NH4} = 286104$$

INFLOWS:

$$\begin{aligned}\text{North_plant_ammonification} &= (0.002 * \text{Temperature}) * \text{North_plant_DON} \\ \text{North_plant_NH4_in} &= \text{Sand_filter_NH4_out}\end{aligned}$$

OUTFLOWS:

$$\begin{aligned}\text{North_plant_nitrification} &= \\ &\text{North_plant_NH4} * \text{North_plant_nitrification_DO_factor} * \text{North_plant_nitrification_salinity_factor} * \\ &\text{North_plant_nitrifiers_factor} * \text{Temp_factor} \\ \text{North_plant_NH4_out} &= \text{North_plant_NH4} \\ \text{North_plant_NH4_plant_uptake} &= \\ &\text{North_plant_NH4} * \text{North_plant_plant_uptake_factor} * \text{North_plant_preference_1}\end{aligned}$$

$$\begin{aligned}\text{North_plant_NO3}(t) &= \text{North_plant_NO3}(t - dt) + (\text{North_plant_nitrification} + \\ &\text{North_plant_NO3_in} - \text{North_plant_NO3_out} - \text{North_plant_denitrification_1} - \\ &\text{North_plant_NO3_plant_uptake}) * dt\end{aligned}$$

$$\text{INIT North_plant_NO3} = 977155$$

INFLOWS:

$$\begin{aligned}\text{North_plant_nitrification} &= \\ &\text{North_plant_NH4} * \text{North_plant_nitrification_DO_factor} * \text{North_plant_nitrification_salinity_factor} * \\ &\text{North_plant_nitrifiers_factor} * \text{Temp_factor} \\ \text{North_plant_NO3_in} &= \text{Sand_filter_NO3_out}\end{aligned}$$

OUTFLOWS:

$$\begin{aligned}\text{North_plant_NO3_out} &= \text{North_plant_NO3} \\ \text{North_plant_denitrification_1} &= \\ &\text{North_plant_NO3} * \text{North_plant_COD_factor} * \text{North_plant_denitrification_salinity_factor} * \\ &\text{North_plant_denitrifier_factor} * \text{Temp_factor} \\ \text{North_plant_NO3_plant_uptake} &= \\ &\text{North_plant_NO3} * \text{North_plant_plant_uptake_factor} * \text{North_plant_preference_2}\end{aligned}$$

$$\begin{aligned}\text{North_plant_PON}(t) &= \text{North_plant_PON}(t - dt) + (\text{North_plant_PON_in} - \\ &\text{North_plant_hydrolysis} - \text{North_plant_PON_sedimentation} - \text{North_plant_PON_accumulation}) * \\ &dt\end{aligned}$$

$$\text{INIT North_plant_PON} = 40935$$

INFLOWS:

$$\text{North_plant_PON_in} = \text{Sand_filter_PON_out}$$

Appendix D (Continued)

OUTFLOWS:

$$\begin{aligned}\text{North_plant_hydrolysis} &= \\ & (\text{North_plant_rate_of_hydrolysis} * \text{North_plant_PON} * (\exp((-0.2) * (20 - \\ & \text{Temperature})))) \\ \text{North_plant_PON_sedimentation} &= \\ & \text{North_plant_PON} * \text{North_plant_rate_of_sedimentation} \\ \text{North_plant_PON_accumulation} &= \\ & \text{North_plant_PON} * \text{North_plant_rate_of_accumulation}\end{aligned}$$

$$\text{Sand_filter_DON}(t) = \text{Sand_filter_DON}(t - dt) + (\text{Sand_filter_DON_in} - \text{Sand_filter_DON_out} - \text{Sand_filter_ammonification}) * dt$$

$$\text{INIT Sand_filter_DON} = 278885$$

INFLOWS:

$$\text{Sand_filter_DON_in} = \text{Solids_tank_DON_out_2}$$

OUTFLOWS:

$$\text{Sand_filter_DON_out} = \text{Sand_filter_DON}$$

$$\text{Sand_filter_ammonification} = (0.002 * \text{Temperature}) * \text{Sand_filter_DON}$$

$$\text{Sand_filter_NH4}(t) = \text{Sand_filter_NH4}(t - dt) + (\text{Sand_filter_NH4_in} + \text{Sand_filter_ammonification} - \text{Sand_filter_NH4_out}) * dt$$

$$\text{INIT Sand_filter_NH4} = 319556$$

INFLOWS:

$$\text{Sand_filter_NH4_in} = \text{Solids_tank_NH4_out_2}$$

$$\text{Sand_filter_ammonification} = (0.002 * \text{Temperature}) * \text{Sand_filter_DON}$$

OUTFLOWS:

$$\text{Sand_filter_NH4_out} = \text{Sand_filter_NH4}$$

$$\text{Sand_filter_NO3}(t) = \text{Sand_filter_NO3}(t - dt) + (\text{Sand_filter_NO3_in} - \text{Sand_filter_NO3_removed} - \text{Sand_filter_NO3_out}) * dt$$

$$\text{INIT Sand_filter_NO3} = 6400367$$

INFLOWS:

$$\text{Sand_filter_NO3_in} = \text{Solids_tank_NO3_out_2}$$

OUTFLOWS:

$$\text{Sand_filter_NO3_removed} = \text{Sand_filter_NO3} * \text{Sand_filter_NO3_removal_eff}$$

$$\text{Sand_filter_NO3_out} = \text{Sand_filter_NO3}$$

$$\text{Sand_filter_PON}(t) = \text{Sand_filter_PON}(t - dt) + (\text{Sand_filter_PON_in} - \text{Sand_filter_PON_out} - \text{Sand_filter_PON_removed}) * dt$$

$$\text{INIT Sand_filter_PON} = 38030$$

INFLOWS:

$$\text{Sand_filter_PON_in} = \text{Solids_tank_PON_out_2}$$

OUTFLOWS:

$$\text{Sand_filter_PON_out} = \text{Sand_filter_PON}$$

$$\text{Sand_filter_PON_removed} = \text{Sand_filter_PON} * \text{Sand_filter_PON_removal_eff}$$

Appendix D (Continued)

$Solids_tank_DON(t) = Solids_tank_DON(t - dt) + (Solids_tank_DON_in - Solids_tank_DON_out_2 - ammonification_solids_tank_NH4) * dt$

INIT Solids_tank_DON = 2371582

INFLOWS:

$Solids_tank_DON_in = Solids_tank_DON_out$

OUTFLOWS:

$Solids_tank_DON_out_2 = Solids_tank_DON$

$ammonification_solids_tank_NH4 = (0.002 * Temperature) * Solids_tank_DON$

$Solids_tank_NH4(t) = Solids_tank_NH4(t - dt) + (Solids_tank_NH4_in + ammonification_solids_tank_NH4 - Solids_tank_NH4_out_2) * dt$

INIT Solids_tank_NH4 = 319556

INFLOWS:

$Solids_tank_NH4_in = Solids_tank_NH4_out$

$ammonification_solids_tank_NH4 = (0.002 * Temperature) * Solids_tank_DON$

OUTFLOWS:

$Solids_tank_NH4_out_2 = Solids_tank_NH4$

$Solids_tank_NO3(t) = Solids_tank_NO3(t - dt) + (Solids_tank_NO3_in - Solids_tank_NO3_out_2 - denitrification) * dt$

INIT Solids_tank_NO3 = 6400367

INFLOWS:

$Solids_tank_NO3_in = Solids_tank_NO3_out$

OUTFLOWS:

$Solids_tank_NO3_out_2 = Solids_tank_NO3$

$denitrification = Solids_tank_NO3 * solids_tank_denitrification$

$Solids_tank_PON(t) = Solids_tank_PON(t - dt) + (Solids_tank_PON_in - Solids_tank_PON_out_2) * dt$

INIT Solids_tank_PON = 323518

INFLOWS:

$Solids_tank_PON_in = Solids_tank_PON_out$

OUTFLOWS:

$Solids_tank_PON_out_2 = Solids_tank_PON$

$South_plant_DON(t) = South_plant_DON(t - dt) + (South_plant_DON_in + South_plant_hydrolysis - South_plant_DON_out - South_plant_ammonification) * dt$

INIT South_plant_DON = 330604

INFLOWS:

$South_plant_DON_in = Solids_tank_DON_out_2$

$South_plant_hydrolysis =$

$(South_plant_rate_of_hydrolysis * South_plant_PON * (exp((-0.2) * (20 - Temperature))))$

Appendix D (Continued)

OUTFLOWS:

$$\text{South_plant_DON_out} = \text{South_plant_DON}$$

$$\text{South_plant_ammonification} = (0.002 * \text{Temperature}) * \text{South_plant_DON}$$

$$\begin{aligned} \text{South_plant_NH4}(t) = & \text{South_plant_NH4}(t - dt) + (\text{South_plant_NH4_in} + \\ & \text{South_plant_ammonification} - \text{South_plant_NH4_out} - \text{South_plant_nitrification} - \\ & \text{South_plant_NH4_plant_uptake}) * dt \end{aligned}$$

$$\text{INIT South_plant_NH4} = 319556$$

INFLOWS:

$$\text{South_plant_NH4_in} = \text{Solids_tank_NH4_out_2}$$

$$\text{South_plant_ammonification} = (0.002 * \text{Temperature}) * \text{South_plant_DON}$$

OUTFLOWS:

$$\text{South_plant_NH4_out} = \text{South_plant_NH4}$$

$$\text{South_plant_nitrification} =$$

$$\text{South_plant_NH4} * \text{South_plant_nitrification_DO_factor} * \text{South_plant_nitrification_salinity_factor} * \text{South_plant_nitrifiers_factor} * \text{Temp_factor}$$

$$\text{South_plant_NH4_plant_uptake} =$$

$$\text{South_plant_NH4} * \text{South_plant_plant_uptake_factor} * \text{South_plant_preference_1}$$

$$\begin{aligned} \text{South_plant_NO3}(t) = & \text{South_plant_NO3}(t - dt) + (\text{South_plant_NO3_in} + \\ & \text{South_plant_nitrification} - \text{South_plant_NO3_out} - \text{South_plant_NO3_plant_uptake} - \\ & \text{South_plant_denitrification}) * dt \end{aligned}$$

$$\text{INIT South_plant_NO3} = 6400367$$

INFLOWS:

$$\text{South_plant_NO3_in} = \text{Solids_tank_NO3_out_2}$$

$$\text{South_plant_nitrification} =$$

$$\text{South_plant_NH4} * \text{South_plant_nitrification_DO_factor} * \text{South_plant_nitrification_salinity_factor} * \text{South_plant_nitrifiers_factor} * \text{Temp_factor}$$

OUTFLOWS:

$$\text{South_plant_NO3_out} = \text{South_plant_NO3}$$

$$\text{South_plant_NO3_plant_uptake} =$$

$$\text{South_plant_NO3} * \text{South_plant_plant_uptake_factor} * \text{South_plant_preference_2}$$

$$\text{South_plant_denitrification} =$$

$$\text{South_plant_NO3} * \text{South_plant_denitrification_salinity_factor} * \text{South_plant_denitrification_COD_factor} * \text{South_plant_denitrifier_factor} * \text{Temp_factor}$$

$$\begin{aligned} \text{South_plant_PON}(t) = & \text{South_plant_PON}(t - dt) + (\text{South_plant_PON_in} - \\ & \text{South_plant_hydrolysis} - \text{South_plant_sedimentation} - \text{South_plant_accumulation}) * dt \end{aligned}$$

$$\text{INIT South_plant_PON} = 45072$$

INFLOWS:

$$\text{South_plant_PON_in} = \text{Solids_tank_PON_out_2}$$

Appendix D (Continued)

OUTFLOWS:

South_plant_hydrolysis =
(South_plant_rate_of_hydrolysis*South_plant_PON*(exp((-0.2)*(20-
Temperature))))
South_plant_sedimentation =
South_plant_PON*South_plant_rate_of_sedimentation
South_plant_accumulation =
South_plant_PON*South_plant_rate_of_accumulation

Active_biomass_for_denitrifiers = Feed_input*(10^{-4.25})*0.16
Active_biomass_for_nitrifiers = Feed_input*(10^{-4.25})*0.24
Apr_11 = 1.87*10⁶
Arr_constant = 1.02
Aug_11 = 2.89*10⁶
COD = Feed_input*10^{-4.5}
COD_half_saturation_constant = 20
crude_protein_percent = 0.40
day_0_to_180 = IF(TIME<90)THEN(day_0_to_90)ELSE(day_91_to_180)
day_0_to_480 = If(TIME<180)THEN(day_0_to_180)ELSE(day_181_to_480)
day_0_to_90 = IF(TIME<30)THEN(Nov_10)ELSE(day_31_to_90)
day_121_to_180 = IF(TIME<150)THEN(Mar_11)ELSE(Apr_11)
day_181_to_270 = IF(TIME<210)THEN(May_11)ELSE(day_211_to_270)
day_181_to_360 = IF(TIME<270)THEN(day_181_to_270)ELSE(day_271_to_360)
day_181_to_480 = IF(TIME<360)THEN(day_181_to_360)ELSE(day_361_to_480)
day_211_to_270 = IF(TIME<240)THEN(Jun_11)ELSE(Jul_11)
day_271_to_360 = IF(TIME<300)THEN(Aug_11)ELSE(day_301_to_360)
day_301_to_360 = IF(TIME<330)THEN(Sep_11)ELSE(Oct_11)
day_31_to_90 = IF(TIME<60)THEN(Dec_10)ELSE(Jan_11)
day_361_to_420 = IF(TIME<390)THEN(Nov_11)ELSE(Dec_11)
day_361_to_480 = IF(TIME<420)THEN(day_361_to_420)ELSE(day_421_to_480)
day_421_to_480 = IF(TIME<450)THEN(Jan_12)ELSE(Feb_12)
day_91_to_180 = IF(TIME<120)THEN(Feb_11)ELSE(day_121_to_180)
Dec_10 = 9.17*10⁵
Dec_11 = 4.00*10⁶
DF_to_MBBR_DON_in = (Drum_filter_DON_out*Drum_filter_to_MBBR_percent_DON)
DF_to_MBBR_NH4_in = Drum_filter_NH4_out*Drum_filter_to_MBBR_percent_NH4
DF_to_MBBR_NO3_in = Drum_filter_NO3_out*Drum_filter_to_MBBR_percent_NO3
DF_to_MBBR_PON_in = (Drum_filter_PON_out*Drum_filter_to_MBBR_percent_PON)
Dissolved_Oxygen = 0.5
DON_excreted = Percent_feed_wasted-PON_lost-NH4_excreted
DON_in_fish_tank = (MBBR_DON_out)+(DON_excreted*feed_waste_as_nitrogen)
DON_in_MBBR = 18

Appendix D (Continued)

DO_factor_denitrification =
Do_half_saturation_constant/(Dissolved_Oxygen+Do_half_saturation_constant)
Do_half_saturation_constant = 0.7
DO_salt_factor = 0.9
DO_Sat = 14.652-(0.41022*Temperature)+(0.007991*(Temperature^2))-
(0.00007777*(Temperature^3))
Drum_filter_to_MBBR_percent_DON = 0.9
Drum_filter_to_MBBR_percent_NH4 = 0.8
Drum_filter_to_MBBR_percent_NO3 = 0.98
Drum_filter_to_MBBR_percent_PON = 0.3
Drum_filter_to_solids_tank_percent_DON = 1-Drum_filter_to_MBBR_percent_DON
Drum_filter_to_solids_tank_percent_NH4 = 1-Drum_filter_to_MBBR_percent_NH4
Drum_filter_to_solids_tank_percent_NO3 = 1-Drum_filter_to_MBBR_percent_NO3
Drum_filter_to_Solids_tank_percent_PON = 1-Drum_filter_to_MBBR_percent_PON
Feb_11 = 1.15*10^6
Feb_12 = 1.51*10^6
Feed_consumed_and_excreted = 1-Feed_lost_to_environment
Feed_lost_to_environment = 0.2
feed_waste_as_nitrogen = (crude_protein_percent*Feed_wasted)/(6.25)
Fish_excretion_as_NH4 = 0.9
Flow_Drum_Filter = 1815508.8
Flow_Fish_Tank = 1683460.8
Flow_Geotube = Flow_Solids_Tank/3
Flow_MBBR = 1683460.8
Flow_North_Bed = Flow_Solids_Tank/3
Flow_Solids_Tank = 132048
Flow_South_Bed = Flow_Solids_Tank/3
Geotube_DON_in_as_concentration = Geotube_DON_in/Flow_Geotube
Geotube_DON_out_as_concentration = Geotube_DON_out/Flow_Geotube
Geotube_DON_removal_eff = 0.37
Geotube_NH4_in_as_concentration = Geotube_NH4_in/Flow_Geotube
Geotube_NH4_out_as_concentration = Geotube_NH4_out/Flow_Geotube
Geotube_NH4_removal_eff = 0.40
Geotube_NO3_in_as_concentration = Geotube_NO3_in/Flow_Geotube
Geotube_NO3_out_as_concentration = Geotube_NO3_out/Flow_Geotube
Geotube_NO3_removal_eff = 0.7
Geotube_PON_in_as_concentration = Geotube_PON_in/Flow_Geotube
Geotube_PON_out_as_concentration = Geotube_PON_out/Flow_Geotube
Geotube_PON_removal_eff = 0.87
Geotube_TN_in_as_concentration =
Geotube_DON_in_as_concentration+Geotube_NH4_in_as_concentration+Geotube_NO3_in_as
_concentration+Geotube_PON_in_as_concentration

Appendix D (Continued)

Geotube_TN_out_as_concentration =
Geotube_DON_out_as_concentration+Geotube_NH4_out_as_concentration+Geotube_NO3_out
_as_concentration+Geotube_PON_out_as_concentration
Half_saturation_constant_for_NH4 = 0.75
Half_saturation_constant_for_NO3 = 0.2
Jan_11 = 1.06*10^6
Jan_12 = 4.71*10^6
Jul_11 = 1.75*10^6
Jun_11 = 2.14*10^6
Mar_11 = 1.43*10^6
Max_specific_growth_rate_for_denitrifiers = 0.015
Max_specific_growth_rate_for_nitrifiers = 0.01
May_11 = 2.21*10^6
MBBR_biofilm_length = 10^-5
MBBR_DON_in_as_concentration = MBBR_DON_in/Flow_MBBR
MBBR_DON_out_as_concentration = MBBR_DON_out/Flow_MBBR
MBBR_first_order_reaction_constant = 0.5
MBBR_media_surface_area_per_volume = 350
MBBR_NH4_diffusion_coefficient = 0.0019
MBBR_NH4_in_as_concentration = MBBR_NH4_in/Flow_MBBR
MBBR_NH4_out_as_concentration = MBBR_NH4_out/Flow_MBBR
MBBR_NO3_in_as_concentration = MBBR_NO3_in/Flow_MBBR
MBBR_NO3_out_as_concentration = MBBR_NO3_out/Flow_MBBR
MBBR_PON_in_as_concentration = MBBR_PON_in/Flow_MBBR
MBBR_PON_out_as_concentration = MBBR_PON_out/Flow_MBBR
MBBR_TN_effluent =
MBBR_DON_out_as_concentration+MBBR_NH4_out_as_concentration+MBBR_NO3_out_as
_concentration+MBBR_PON_out_as_concentration
MBBR_TN_influent =
MBBR_DON_in_as_concentration+MBBR_NH4_in_as_concentration+MBBR_NO3_in_as_co
ncentration+MBBR_PON_in_as_concentration
MBBR_volume = 72.61
MBBR_zero_order_reaction_constant = 50
NH4_excreted = Feed_consumed_and_excreted*Fish_excretion_as_NH4*Percent_feed_wasted
NH4_in_fish_tank = (MBBR_NH4_out)+(NH4_excreted*feed_waste_as_nitrogen)-
(Passive_nitrification*MBBR_NH4_out)
NH4_in_MBBR = 0.2
NO3_in_fish_tank = (MBBR_NO3_out)+(Passive_nitrification*MBBR_NH4_out)
NO3_in_MBBR = 27.9
North_plant_COD_factor = COD/(COD+COD_half_saturation_constant)
North_plant_denitrification_salinity_factor = (15200)/(Salinity+15200)
North_plant_denitrifier_factor =
(Active_biomass_for_denitrifiers*Max_specific_growth_rate_for_denitrifiers)/(Yield_coefficien
t_for_denitrifiers*Half_saturation_constant_for_NO3)

Appendix D (Continued)

North_plant_DO_half_saturation_constant = 0.7
North_plant_nitrification_DO_factor =
DO_out/(DO_out+North_plant_DO_half_saturation_constant)
North_plant_nitrification_salinity_factor = (14200)/(Salinity+14200)
North_plant_nitrifiers_factor =
(Max_specific_growth_rate_for_nitrifiers*Active_biomass_for_nitrifiers)/(Half_saturation_constant_for_NH4*Yield_coefficient_for_nitrifiers)
North_plant_plant_uptake_factor = 0.0210
North_plant_preference_1 = 0.75
North_plant_preference_2 = 1-North_plant_preference_1
North_plant_rate_of_accumulation = 0.00754
North_plant_rate_of_hydrolysis = 0.06
North_plant_rate_of_sedimentation = 0.01
North_Plant_TN_effluent =
NP_DON_out_as_concen+NP_NH4_out_as_concen+NP_NO3_out_as_concen
North_Plant_TN_influent =
NP_DON_in_as_concen+NP_NH4_in_as_concen+NP_NO3_in_as_concen+NP_PON_in_as_concen
North_plant_volume = 6370
Nov_10 = 7.75*10⁵
Nov_11 = 2.38*10⁶
NP_DON_in_as_concen = North_plant_DON_in/Flow_North_Bed
NP_DON_out_as_concen = North_plant_DON_out/Flow_North_Bed
NP_NH4_in_as_concen = North_plant_NH4_in/Flow_North_Bed
NP_NH4_out_as_concen = North_plant_NH4_out/Flow_North_Bed
NP_NO3_in_as_concen = North_plant_NO3_in/Flow_North_Bed
NP_NO3_out_as_concen = North_plant_NO3_out/Flow_North_Bed
NP_PON_in_as_concen = North_plant_PON_in/Flow_North_Bed
Oct_11 = 3.43*10⁶
Passive_nitrification = 0.1
Percent_feed_consumed = 0.30
Percent_feed_wasted = 1-Percent_feed_consumed
PON_in_fish_tank = (MBBR_PON_out)+(PON_lost*feed_waste_as_nitrogen)
PON_in_MBBR = 1.44
PON_lost = Feed_lost_to_environment*Percent_feed_wasted
Salinity = 18000
Sand_filter_NO3_removal_eff = 0.8
Sand_filter_PON_removal_eff = 0.85
Sep_11 = 2.84*10⁶
SF_DON_out_as_concen = Sand_filter_DON_out/Flow_North_Bed
SF_NH4_out_as_concen = Sand_filter_NH4_out/Flow_North_Bed
SF_NO3_out_as_concen = Sand_filter_NO3_out/Flow_North_Bed
SF_PON_out_as_concen = Sand_filter_PON_out/Flow_North_Bed

Appendix D (Continued)

SF_TN_out_as_concen =
SF_DON_out_as_concen+SF_NH4_out_as_concen+SF_NO3_out_as_concen+SF_PON_out_as
_concen
solids_tank_denitrification = 0.13
Solids_tank_DON_out =
((Drum_filter_DON_out*Drum_filter_to_solids_tank_percent_DON)/3)
Solids_tank_NH4_out = (Drum_filter_NH4_out*Drum_filter_to_solids_tank_percent_NH4/3)
Solids_tank_NO3_out = Drum_filter_NO3_out*Drum_filter_to_solids_tank_percent_NO3*(1-
solids_tank_denitrification)
Solids_tank_PON_out = (Drum_filter_PON_out*Drum_filter_to_Solids_tank_percent_PON)/3
South_plant_denitrification_salinity_factor = (15200)/(Salinity+15200)
South_plant_denitrification_COD_factor = COD/(COD+COD_half_saturation_constant)
South_plant_denitrifier_factor =
(Max_specific_growth_rate_for_denitrifiers*Active_biomass_for_denitrifiers)/(Half_saturation
_constant_for_NO3*Yield_coefficient_for_denitrifiers)
South_plant_DO_half_saturation_constant = 0.7
South_plant_nitrification_DO_factor =
DO_out/(DO_out+South_plant_DO_half_saturation_constant)
South_plant_nitrification_salinity_factor = (14200)/(Salinity+14200)
South_plant_nitrifiers_factor =
(Max_specific_growth_rate_for_nitrifiers*Active_biomass_for_nitrifiers)/(Half_saturation_cons
tant_for_NH4*Yield_coefficient_for_nitrifiers)
South_plant_plant_uptake_factor = 0.0212
South_plant_PON_in_as_concen = South_plant_PON_in/Flow_South_Bed
South_plant_preference_1 = 0.75
South_plant_preference_2 = 1-South_plant_preference_1
South_plant_rate_of_accumulation = 0.0093
South_plant_rate_of_hydrolysis = 0.06
South_plant_rate_of_sedimentation = 0.01
South_plant_volume = 6370
SP_DON_in_as_concen = South_plant_DON_in/Flow_South_Bed
SP_DON_out_as_concen = South_plant_DON_out/Flow_South_Bed
SP_NH4_in_as_concen = South_plant_NH4_in/Flow_South_Bed
SP_NH4_out_as_concen = South_plant_NH4_out/Flow_South_Bed
SP_NO3_in_as_concen = South_plant_NO3_in/Flow_South_Bed
SP_NO3_out_as_concern = South_plant_NO3_out/Flow_South_Bed
SP_TN_effluent =
SP_DON_out_as_concen+SP_NH4_out_as_concen+SP_NO3_out_as_concern
SP_TN_influent =
South_plant_PON_in_as_concen+SP_DON_in_as_concen+SP_NH4_in_as_concen+SP_NO3_i
n_as_concen
ST_DON_concen = Flow_Solids_Tank/Solids_tank_DON_out_2
ST_NH4_concen = Flow_Solids_Tank/Solids_tank_NH4_out_2
ST_NO3_concen = Flow_Solids_Tank/Solids_tank_NO3_out_2

Appendix D (Continued)

ST_PON_concen = Flow_Solids_Tank/Solids_tank_PON_out_2

Temperature = SINWAVE(7.95,365)+23.35

Temp_factor = Arr_constant^(Temperature-20)

VSS = Feed_input*10^-4.25

Yield_coefficient_for_denitrifiers = 0.25

Yield_coefficient_for_nitrifiers = 0.1