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A SWMM-5 Model of a Denitrifying Bioretention System to Estimate Nitrogen Removal From Stormwater Runoff

Michelle D. Masi
University of South Florida, mbonewit@mail.usf.edu

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A SWMM-5 Model of a Denitrifying Bioretention System to Estimate Nitrogen Removal From Stormwater Runoff

by

Michelle Masi

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of the requirements for the degree of
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Major Professor: Sarina Ergas, Ph.D.
Jeffrey Cunningham, Ph.D.
Daniel Yeh, Ph.D.

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List of Acronyms

BMPs	best management practices
BOD	biochemical oxygen demand
COD	chemical oxygen demand
DO	dissolved oxygen
LID	low impact development
MCL	maximum contaminant level
NOx	nitrogen oxides
Org N	organic nitrogen
SJWMD	St. John’s Water Management District
SWFWMD	SW Florida Water Management District
SWMM5	Storm Water Management Model 5
TKN	Total Kjeldahl Nitrogen
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VSS	volatile suspended solids
WQS	water quality standards

List of Symbols

V	volume of the cell (m^3)
TKN_i	influent TKN concentration (mg/L)
TKN_{eff}	effluent TKN concentration (mg/L)
$NO_{3,eff}$	effluent nitrate concentration (mg/L)
$NO_{3,i}$	influent nitrate concentration (mg/L)
R_TKN_i	Concentration of reacted TKN_i (mg/L)
k_1 and k_2	rate of nitrification and denitrification, respectively (1/T)
HRT_1 and HRT_2	hydraulic residence time (hours)

Abstract

This research estimates nitrogen removal from stormwater runoff using a denitrifying bioretention system using the USEPA Storm Water Management Model Version 5 (SWMM-5). SWMM-5 has been used to help planners make better decisions since its development in 1971. A conventional bioretention system is a type of Low Impact Development (LID) technology, which designed without a media layer specifically for achieving nitrogen removal. More recently studies have showed that high TN removal efficiencies are possible when incorporating a denitrification media layer. These systems are known as denitrifying bioretention systems, or alternative bioretention systems. LID projects are currently being designed and developed in Sarasota County, Florida. These projects include a bioretention cell retrofit project on Venice East Blvd., in Venice, FL where thirteen bioretention cells will be developed. Although implementation of LID has already begun in southwest Florida, little research exists on whether these systems are effective at reducing non-point sources of nutrients. Therefore, the overall goal of this research project was to investigate the performance of a proposed bioretention system in Venice, FL to treat non-point sources of nitrogen from stormwater runoff.

An alternative bioretention cell (ABC) model was designed to conceptually address water routing through a layered bioretention cell by separating the model into treatment layers- the layers where the nitrification and denitrification reactions are expected to occur within an alternative bioretention system (i.e., nitrification is assumed to occur in the sand media layer, and denitrification in the wood chip media layer). The bioretention cell configuration was based largely on the development plans provided by Sarasota County; however, the configuration incorporated the same electron donor media for denitrification that was used in a prior study (i.e., wood chips). Site-specific input parameters needed to calibrate the ABC model were obtained from laboratory analyses, the literature, and the US Geological website (websoilsurvey.nrcs.usda.gov).

Using a mass balance approach, and the hydraulic residence time (HRT) values from the results of a previous study, first-order loss rate coefficients for both nitrification and denitrification (k_1 and k_2, respectively) were estimated. The rate coefficients were then used to develop treatment expression for nitrification and denitrification reactions. The treatment expressions were used to estimate the annual load reductions for TKN, NO_3^--N, and TN at the Venice East Blvd. bioretention retrofit site.

Six storm events were simulated using a range of nitrogen concentrations. The simulation results showed minimal nitrification removal rates for storm events exceeding 1 inch, due to the planned bioretention system area being only 1% of the subcatchment area. A new ABC model was created (based on EPA bioretention cell sizing guidelines), to be 6% of the subcatchment area. Both systems were used to estimate TN removal efficiencies. The larger sized ABC model results showed average TKN, NO_3^--N and TN reductions of 84%, 96%; and 87%, respectively; these are comparable to results from similar studies. Results indicate that adequate nitrogen attenuation is achievable in the alternative bioretention system, if it is sized according to EPA sizing guidelines (5-7%)

Chapter One:

Introduction

Regulation of point source pollution by the Clean Water Act, the EPA's National Pollutant Discharge Elimination System (NPDES), has led to a decrease in pollution in our waterways. However, there are still pollutant issues that must be addressed. A point-source pollutant is waste matter from an identifiable source, such as polluted water from a wastewater treatment plant. A non-point-source pollutant can come from many diffuse sources, such as atmospheric deposition, agricultural runoff, or stormwater runoff [USEPA, 2005]. Recent research indicates that non-point-source pollution is still heavily impacting aquatic ecosystems across the United States [USEPA, 2007]. The topic of this project is the control of non-point source pollution in stormwater runoff, which is a concern due to its effect on human health and the environment.

According to the Florida Department of Environmental Protection (FDEP), as rainwater falls onto pervious surfaces in Florida, on average 50% will evaporate, 30% will runoff and will enter a nearby surface water, and 20% will infiltrate into the ground [FDEP, 2010]. However, in urban areas across the US, these numbers differ significantly. As concrete infrastructure and urban development continue to create impervious zones, stormwater runoff is now being considered a major contributor to non-point source pollution. In fact, urbanization alters all parts of the hydrologic cycle, so much so that no simple analysis of its effects on groundwater is possible [Lerner, 1990].

Stormwater runoff contains a number of contaminants, including nutrients (e.g., nitrogen and phosphorus), metals, oil and grease, organics, solids, and microorganisms [USEPA, 2005]. The nutrients in these discharges over-load receiving water bodies, which can lead to eutrophication (i.e., excess algal growth) [Campbell, 2005]. Eutrophication is a key driver in a number of environmental problems in aquatic ecosystems including reduced light penetration resulting in seagrass mortality, increases in harmful algal blooms, and hypoxic and anoxic conditions.

Another major concern with the transport of nitrogen compounds in stormwater runoff is the potential contamination of drinking water sources. Methemoglobanemia, or blue baby syndrome, is a human health hazard that is caused by high concentrations of NO_3^- in drinking water. “The nitrate ion binds to hemoglobin (the compound which carries oxygen in blood to tissues in the body), and results in chemically-altered hemoglobin (methemoglobin) that impairs oxygen delivery to tissues, resulting in a blue color of the skin” [USEPA, 2007].

Control of stormwater runoff can be challenging in urban areas, as most projects must be retrofitted to suit the needs of the developed community. Stormwater management has been addressed by regulators for many years, and more recent management practices have begun to incorporate the idea of using a train of treatment technologies (i.e., multiple treatment processes) or best management practices (BMPs). BMPs are often site-specific, and should incorporate techniques to reduce non-point source pollution to an acceptable level. Some examples of BMPs that can be used to decrease non-point source pollution associated with stormwater runoff are: grassed swales, constructed wetlands and treatment lagoons. Although these technologies can help reduce flows, they are not typically designed to achieve nitrogen removal through denitrification. There is a lot of research that indicates the benefit of using BMPs for stormwater management; however, varying regulations will require site-specific criteria to reduce different types of nutrients.

The difference between BMPs and Low Impact Development (LID) technologies is that LID focuses on restoring pre-development hydrologic flows by treating runoff onsite and promoting infiltration into the ground [Monroe and Vince, 2008]. Most urban areas control and treat stormwater runoff using a single engineered stormwater pond, which often drains into a larger water body. By incorporating LID technologies in urban areas, stormwater runoff is treated at its source [Monroe and Vince, 2008]. Some examples of LID technologies and their uses can be seen in Table 1.1.

Increased concrete infrastructure in urban areas results in an increase in stormwater runoff. This runoff is often loaded with non-point-source pollutants, like nitrogen [Monroe and Vince, 2008]. Bioretention cells (the focus of this project)are an exciting new tool stormwater regulators can use, and other interested professionals, that are based on site and nutrient specific needs to reduce non-point sources of nitrogen pollution. The removal of nitrogen from stormwater runoff in an alternative bioretention cell is achieved as the runoff percolates through defined media layers, specifically in place to achieve different N transformation processes. Denitrification is achieved when the nitrified water is conveyed through the submerged denitrification region (this is explained in more detail in the subsequent chapter).

Table 1.1. Summary of LID technologies and their intended uses [adapted from EPA, 2000].

Low Impact Development Technology	**General Use(s)**
Bioretention Cells/Bioswales*	Groundwater recharge, restore pre-urbanized hydrologic flows and reduce nutrient loading to surface water and groundwater
Vegetated Roofs	Restore hydrologic flows, and reduce heat island effect in urban areas
Permeable Pavement	Restore hydrologic flows in urban areas
Rain Barrels	Rainwater harvesting, water reuse

(* this technology is the topic of this research project)

Research Objectives

The focus of this project is the control of nitrogen in stormwater runoff using LID technologies in southwest Florida; specifically the use of bioretention systems. The overall goal of this research project was to investigate the performance of a proposed bioretention system in Venice, FL to treat non-point sources of nitrogen from stormwater runoff. The methods used to reach these objectives include:

1. Gather rainfall data, inputs and parameters for the proposed bioretention case study site in Venice, FL, needed to calibrate the SWMM-5 model.
2. Estimate rate coefficient values (k_1 and k_2) for the rate of nitrification and denitrification using a previous study.
3. Develop a conceptual model to address flow as it moves through the different layers in an alternative bioretention cell, and where nitrification and denitrification will occur within these layers.
4. Using the EPA’s SWMM5 Modeling software, develop an alternative bioretention cell (ABC) model to estimate nitrogen removal from stormwater runoff.

Scope of Work

In 2008/2009 Sarasota County completed a draft *Low Impact Development Manual* [Sarasota County, 2009]; this manual will be the first of its kind once finalized. Although the use of LID technologies in the northern US is becoming more common, implementation of LID in southwest Florida has lagged because of the extreme differences in Florida's geographical features (e.g. hydrogeology, climate, etc.), compared to the northwestern US, where LID was developed. Sarasota County is taking the initiative to incorporate LID technologies into many of their capital improvement projects. The County has just completed a preliminary design for a water quality retrofit project in Venice, FL, that will incorporate thirteen bioretention cells, or bioswales. The project site runs along a residential, four-lane curbed road on Venice East Blvd., which drains into Alligator Creek, an impaired body of water.

The final design and construction of this project will be co-funded by the Southwest Florida Water Management District (SWFWMD) and Sarasota County. The estimate of the probable cost of the construction (based on Sarasota County's budget provided by Jack Merriam, an Environmental Manager in Sarasota County), is $603,556, and the County portion will come from a one penny sales tax approved by County voters for capital improvement projects. The SWFWMD will be contributing a portion of the project funding from their Cooperative Grant program.

Three of the thirteen bioretention cells currently planned for development in Venice, FL are proposed to be redesigned and monitored for future study by USF. A map of the Venice East retrofit site can be viewed in Figure 1.1. The three redesigned bioretention cells will be placed side-by-side, and run parallel to one another. Each of the three cells will be fitted with an outlet pipe, which will drain into a retention ditch that runs perpendicular to Venice East Blvd., and drains into the Alligator Creek watershed; in order to analyze water quality characteristics.

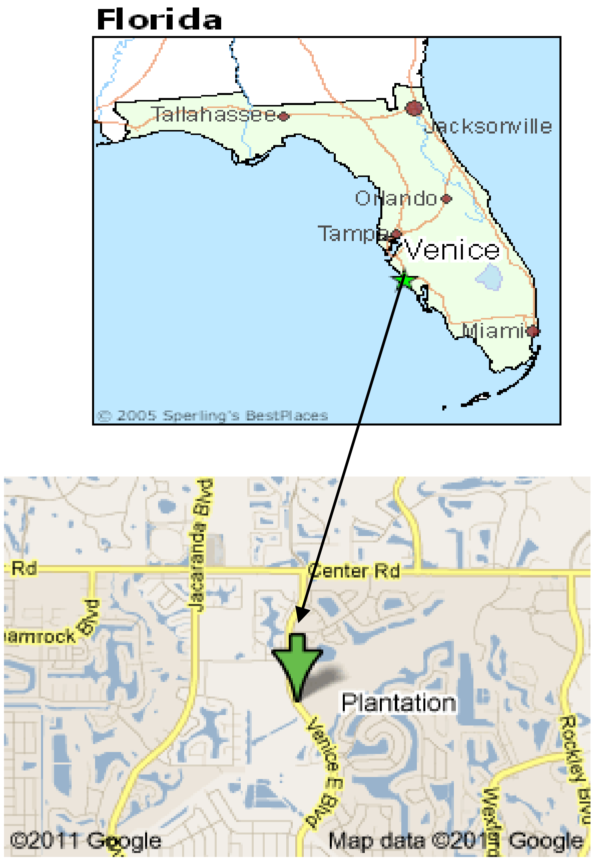

Figure 1.1. Map of Florida; aerial map shows the exact location of retrofit site [Google Maps, 2011].

Chapter Two:

Background

This chapter begins with a discussion on the biological processes involved in the nitrogen cycle. The subsequent section will address some of the major environmental impacts and human health hazards associated with excess nitrogen loading to aquatic ecosystems and drinking water supplies. A literature review will follow, which will outline some relevant low impact development (LID) technologies being used to control non-point sources of pollution from stormwater runoff, as well as to provide some insight on local projects in Southwest Florida (SWFL) that are utilizing LID technologies. The chapter will conclude with a discussion of the benefits of treating non-point source pollution from stormwater runoff through implementation of LID technologies in SWFL, and the benefit of using stormwater management software to estimate pre- vs. post-development nitrogen loading (lbs/event).

The Nitrogen Cycle

The nitrogen cycle addresses the different species of nitrogen and how they are "interconnected in the air, soil, water and in living organisms" [Soil Health, 2008]. It is considered a cycle because the nitrogen never actually leaves the system. Various nitrogen transformation processes simply change the form of the nitrogen. Nitrogen is a very important constituent on a cellular level, and it exists in many oxidation states. Nitrogen gas (N_2) is the most abundant form of nitrogen in the atmosphere and accounts for 78% (by volume) of the air we breathe [Davis and Masten, 2004]. However, only a few prokaryotes are able to use nitrogen in its gaseous form (N_2); therefore, the cycling of nitrogen is an essential process that is necessary to sustain life [Madigan et al. 2009].

Some transformations of nitrogen happen to be energy yielding, while other reactions are merely to obtain nitrogen for structural synthesis [Allan, 1995]. Nitrogen fixation of dissolved inorganic nitrogen is an example of a process to obtain nitrogen for structural synthesis; whereas nitrification and denitrification are examples of transformations “where bacteria obtain energy by using ammonia as a fuel or nitrate as an oxidizing agent” [Day et al., 1989]. There are 5 major processes involved in the nitrogen cycle; ammonification, nitrification, denitrification, nitrogen fixation and nitrogen immobilization. Nitrification and denitrification are the key chemical reactions related to this research, and will be discussed in subsequent sections.

Ammonification is the transformation of organic nitrogen (Org N) to ammonium, an inorganic for of nitrogen [Soil Health, 2008]. Various soil organisms can carry out the ammonification process, by “using carbon and energy from the breakdown of organic matter” in the soil, “while nitrogen is released at the same time” [Soil Health, 2008]. Ammonification can also occur when an animal excretes nitrogen in its organic form (Org N), in the form of urea ($CO(NH_2)_2$), which is transformed to ammonium through enzymatic hydrolysis [Muck, 1982]. The urease enzyme is responsible for the hydrolysis of urea, and is found in soils and feces [Muck, 1982; Havlin et al., 1999]. The ammonification reaction is significantly influenced by: (1) warm temperatures ranging from 40-60°, (2) near neutral pH and (3) soils that are moist enough for plant growth [Alexander, 1991; Muck, 1982; Havlin et al. 1999]. The optimum rate of ammonification generally occurs when the moisture content of the soil is between 50-75% of the water holding capacity for the soil, and the rate will generally decrease as the moisture content diminishes [Alexander, 1991].

Ammonia is positively charged, and therefore it adsorbs well to soil particles; making it less likely to leach into the underlying aquifer. However, in excess, ammonia can cause detrimental effects to both human health and aquatic ecosystems. In most surface waters, “total ammonia concentrations greater than about 2 milligrams per liter are toxic to aquatic animals” [Mueller and Helsel, 1996], although this can be different for different species. Studies have analyzed the “toxicity of ammonia to freshwater vegetation”, and “have shown that concentrations greater than 2.4 milligrams of total ammonia (i.e., ammonia plus ammonium) per liter inhibit photosynthesis and growth in algae” [World Health Organization, 1986]. “Nitrogen fixation is the conversion of nitrogen gas (N_2) to ammonia (NH_3^+) either by free living bacteria in soil or water, or by bacteria in symbiotic association with plants; legume symbiosis” [Soil Health, 2008].

Symbiotic relationships between legumes species (i.e., beans, peas, clovers) is accomplished with N_2 fixing microorganisms (i.e., *Rhizobium* species) living within the legume roots [Soil Health, 2008]. The microorganisms receive carbohydrates, as well as optimal living conditions, while the roots absorb the N_2 fixed by the microorganisms [Harrison, 2003]. Nitrogen fixation can also occur chemically in the atmosphere during lightning events, and during the manufacturing of nitrogen containing fertilizers. Most of the recycled nitrogen on earth is in a fixed form, such as ammonia (NH_3) and nitrate (NO_3^-).

Nitrogen immobilization, sometimes referred to as nitrogen uptake or assimilation, is the process where the microbes incorporate the nitrogen and convert it to organic nitrogen [Soil Health, 2008]. Immobilization occurs in parallel with ammonification; meaning that these reactions take place simultaneously. Both plants and microorganisms carry out the process of nitrogen immobilization to gain the elemental form nitrogen that is necessary to sustain life. The nitrogen converted in this process is used to form proteins, nucleic acids and other Org N compounds [King, 1987].

Nitrification is the process in the nitrogen cycle that oxidizes ammonium (NH_4^+) into nitrite (NO_2^-) and then to nitrate (NO_3^-) [Soil Health, 2008]. This transformation occurs readily in well-drained soils at neutral pH [Madigan, 2009]. Although nitrate is readily assimilated by plants, it is also water-soluble and is rapidly leached or denitrified during heavy rainfall [Madigan, 2009]. Nitrification is a two step process carried out by a relatively small number of organisms found in soil. The first step in the nitrification process is the conversion of ammonia nitrogen to nitrite (equation 2.2). The second step (equation 2.3) is the conversion of nitrite to nitrate, as shown in the reaction below [Rittmann and McCarty, 2001]:

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O \qquad (2.1)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \qquad (2.2)$$

Overall balanced reaction:

$$NH_4^+ + 1.815O_2 + 0.1304CO_2 \rightarrow$$
$$0.0261C_5H_7O_2N + 0.973NO_3^- + 1.973H^+ + 0.921H_2O \qquad (2.3)$$

Nitrosomonas bacteria, which are aerobic autotrophs, are responsible for the conversion in step one. During the conversion, these bacteria consume large quantities of dissolved oxygen (DO), while reducing the alkalinity. *Nitrobacter*, which are also aerobic autotrophs, are responsible for converting the nitrite to nitrate. *Nitrobacter* have a faster growth rate than *Nitrosomonas,* therefore, once the ammonia is converted to nitrite, the conversion to nitrate occurs rapidly.

Denitrification is the transformation pathway in the nitrogen cycle that completely removes nitrogen the bioretention cell, with its end product being N_2 [Harrison, 2003]. The nitrate reduction reaction includes intermediate steps in which nitrate is transformed to nitrite, to nitric oxide, to nitrous oxide,and then to N_2 [Metcalf and Eddy, 2003]:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \qquad (2.4)$$

A specialized group of bacteria are responsible for the process of denitrification. These bacteria are known as denitrifiers (Rittman and McCarty, 2001). Denitrifiers are facultative aerobes; which means that they have the ability to shift from aerobic to nitrate respiration when oxygen becomes limited. The “denitrifying bacteria use the nitrate as an electron acceptor to oxidize organic matter anaerobically” [Madigan, 2009]. In well oxygenated sediments, the denitrification process will be limited. However, in the deeper sediments towards the bottom of the bioretention cell, where oxygen levels are low, the environmental conditions will be favorable for the denitrification process.

In order for nitrate to be reduced to nitrogen gas there must be an available electron donor, or an inorganic electron donor such as sulfur or carbon. Equation 2.4 represents an example of a reaction using an organic carbon source (Sawyer et al., 2003). Equation 2.5 represents the overall autotrophic denitrification reaction when elemental sulfur (S^0) is utilized as the electron donor (Bachelor and Lawrence, 1978).

$$C_{10}H_{19}O_3N + 10\ NO_3^- \rightarrow 5\ N_2 + 10\ CO_2 + 3\ H_2O + NH_3 + 10\ OH^- \quad (2.5)$$

$$1\ S^0 + 0.4\ CO_2 + NO_3^- + 0.76\ H_2O + 0.08\ NH_4^+ \rightarrow$$
$$0.08\ C_5H_7O_2N + 1.1\ SO_4^{-2} + 0.5\ N_2 + 0.781\ H^+ \quad (2.6)$$

Hazards Associated with Excess Nitrogen in Stormwater Runoff

One major contributor to non-point source pollution is from storm water runoff. The pollutants found in storm water runoff negatively impact drinking water supplies, recreational fishing areas and wildlife [USEPA, 2010]. In the 1970's the USEPA initiated the Pollution Act, also known as the Clean Water Act, which mandated that all water bodies in the US be suitable for swimming and fishing purposes [CWA, 1972]. In 1998 the EPA assessed approximately 32% of US surface waters to address water quality concerns. Of those assessed, 40% of US streams, lakes and estuaries were not meeting EPA's water quality standards (WQS) to support recreational activities [USEPA, 2000]. The major pollutants found in these impaired water bodies were non-point source pollutants. Storm water is an example of a non-point source pollutant. As heavy rain washes down concrete infrastructure it picks up contaminants such as sediments, nutrients, heavy metals, bacteria, oils and greases; flushing them into receiving water ways. These contaminants are harmful to both humans and wildlife.

According to the St. Johns River Water Management District in Florida, nearly 80% of external nutrient loading is conveyed by runoff [SJWMD, 2006]. Agricultural stormwater runoff plays a major role in the contamination of aquatic ecosystems across the US, and in Florida. Nearly all of the estimated 242 million acres of land used to grow crops in the US is maintained with pesticides and fertilizers [USDA, 2002]. Fertilizers contain high concentrations of nitrogen and phosphorus (plant food). Pesticides contain heavy metals such as arsenic, mercury and lead. Although the application of fertilizers and pesticides may be essential to provide adequate food supplies to expanding populations, in excess these harmful contaminants are being carried away by heavy rains; and are ending up in our surface and groundwater.

Nitrogen and Phosphorus rich pesticides and fertilizers are frequently used in urban areas as well. In fact many Americans use these products to fertilize their lawns. Throughout Southwest Florida, annual plants, vegetables and lawns sometimes need additional nutrients from fertilizer. When these nutrients are picked up by stormwater in urban areas they accumulate, because the runoff is not able to undergo pre-development hydrologic processes [OEC, 2010]. Figure 2.1 illustrates pre- vs. post-development hydrologic flows. The figure shows that in urban areas there is an increase in surface runoff, due to a decrease in porous surfaces. In large cities impervious infrastructure can sprawl for miles. Therefore, it is not uncommon to find receiving water ways (e.g., rivers, lakes and streams) impaired; due to a flux of harmful pollutants during storm events.

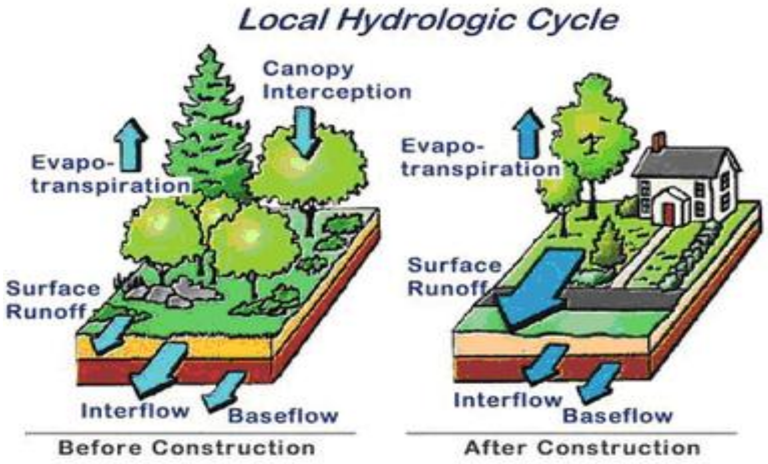

Figure 2.1. Pre-development vs. post-development hydrologic cycle [Maryland DEP, 2010].

Nutrients, such as nitrogen, can also be distributed to lakes and streams via atmospheric deposition. The USEPA list three types of atmospheric deposition processes; wet deposition, where pollutants are distributed through rain or snow; dry deposition, where winds move particles through the air; and gas absorption, the dominant atmospheric deposition process for many semivolatile persistent bioaccumulative toxic pollutants [USEPA, 2010]. Lightning plays a role in nitrogen absorption process in the atmosphere. "The enormous energy of lightning breaks nitrogen molecules and enables their atoms to combine with oxygen in the air forming nitrogen oxides (NO_x)" [Kimball, 2008]. These nitrogen oxides will then dissolve in precipitation, forming NO_3^- ions, which are then transported to the soil during a storm [NPAP, 2010].

Nitrate ions are negatively charged (NO_3^-), and therefore they do not adhere well to the soil particles (which are also negatively charged). Nitrogen can be very harmful to the human health and aquatic ecosystems, as elevated levels of nitrate (NO_3^-) and/or nitrite (NO_2^-) in drinking water can cause methemoglobinemia, or "Blue Baby Syndrome" in infants. When infants ingest nitrate it can be reduced to nitrite in the body, which can transform the oxygen binding hemoglobin into non-oxygen binding methemoglobin [Fewtrell, 2004]. Because of this health concern, the United States Environmental Protection Agency (USEPA) set a drinking water maximum contaminant level (MCL) at 10 mg/L and 1 mg/L (as nitrogen) for $NO3^-$ and $NO2^-$, respectively [USEPA, 2003].

The impact of nitrogen on human health is undeniable; what's more, increased nitrogen and phosphorus in aquatic ecosystems can cause environmental degredation to aquatic ecosystems as well. When nitogen in the form of ammonium (NH_4^+) enters an aquatic ecosystem, the result can be an increase in aquatic organisms, which can decrease dissolved oxygen (DO) levels in the water due to the oxygen demand when NH_4^+ is converted to NO_3^- through the process of nitrification [Metcalf and Eddy, 2003]. The loss of DO results in poor water quality conditions for aquatic life, and can leave an aquatic ecosystem in despair.

In 2006, a local consulting firm, Janicki Environmental, published an analysis of the impacts of Nitrogen loading on seagrass coverage in the Tampa Bay estuary. Seagrass is beneficial to aquatic ecosystems, as it provides habitat to as many as 40,000 fish species, and 50 million small invertebrates; and it filters suspended solids out of the water column, improving water clarity [Hill, 2002]. However, seagrass (like many other plants) cannot tolerate over-enrichment from concentrated runoff. In the 1970's, due to increased urbanization and industrialization of the Tampa Bay area, the receiving water ways (the Tampa Bay and its surrounding water bodies) saw an increase nitrogen and phosphorus loading [Pribble et al., 2001, Poe et al., 2005].

After strict water quality criteria were mandated by the CWA for point-source polluters, the Tampa Bay estuary began to see an increase in sea grass coverage. However, due to non-point source pollution remaining untamed, today only 70% of the seagrass has been restored in this region [Janicki and Greening, 2006]. State and local regulations now aim to reduce the impact of nitrogen loading to the bay, by reducing non-point sources of pollution from stormwater runoff [SWFWMD, 2010].

Stormwater Management: Low Impact Development Technologies

Approximately 80% of the US population lives in coastal communities and Southwest Florida has experienced some of the nation's most rapid coastal development.

Dramatic landscape changes have occurred since the time of early settlement of Southwest Florida - records show that the one square mile aggregate urban area of the 1890s grew to more than 80 square miles by the 1990s [SWFWMD, 2006]. During this same period, vegetated uplands (e.g. forest, shrub, and brushland) decreased by 76% [SWFWMD, 2006]. These changes have had a profound effect on the hydrologic cycle; pervious spaces have been converted to land uses with increased impervious surfaces, resulting in increased runoff volumes and pollutant loadings. Adding to the problems of urban runoff is the fact that Southwest Florida is a karst region, where porous carbonate rocks create a highly heterogenous aquifer system with rapid ground water movement and recharge [USGS, 2001]. In karst regions, large volumes of stormwater rapidly undermine the bedrock, thereby increasing groundwater pollution [USGS, 2001]. In addition, the region is highly dependent on groundwater resources, with nearly 80% of the 1 billion gallons of water used daily by residents coming from the Floridian aquifer [SWFWMD, 2001].

A number of BMPs are used to control stormwater runoff, including structural BMPs (previously listed) as well as non-structural BMPs such as education and maintenance programs [Shoemaker et al. 2002]. Conventional stormwater ponds are designed to minimize flooding by channeling runoff to a depressed area. Water then either slowly infiltrates the underlying soil (retention pond) or is gradually released to an adjacent surface water body (detention pond). Conventional stormwater ponds can be designed to both control flooding and improve water quality [University of Wisconsin, 2005]; however, some studies have shown little improvement in nutrient loadings in these systems [Mallin et al., 2000].

“Low impact development (LID) is an approach to land development (or re-development) that works with nature to manage stormwater as close to its source as possible. LID employs principles such as preserving and recreating natural landscape features and minimizing impervious surfaces” [City of Poulsbo, 2009]. LID is economically appealing to stormwater management professionals, as it is relatively inexpensive to retrofit a current site. Additionally, LID provides aesthetic appeal to some urbanized areas, which may have previously been a sore spot in the community.

LID is gaining popularity in urban cities as it emphasizes on-site treatment and infiltration of stormwater, in contrast to “conventional stormwater controls, which collect stormwater from impervious surfaces and transport the flow off site through buried pipes to treatment facilities or directly to receiving” bodies of water [Econet, 2010]. The use of LID practices is beneficial to the environment because it reduces disturbance of the development area and the preservation of the pervious landscape. It can also be less cost intensive than traditional stormwater control mechanisms [USEPA, 2000]. LID techniques can be used in retrofitting existing urban areas with pollution controls, as well as in new developments [Byrne, 2008]. The following are LID technologies that are being used by stormwater management professionals to diminish non-point source pollution from stormwater runoff:

- Vegetated Rooftops
- Permeable Pavement
- Rain Barrels
- Bioretention Cells/Bioswales (addressed in this research)

Vegetated rooftops, or green roofs, get their name from their design features; they’re constructed in multiple layers (Figure 2.2), consisting of a vegetated layer, media, a geotextile layer and a synthetic drain layer [USEPA, 2000]. The most notable feature of vegetated rooftops is the inclusion of the natural flora and soil/media components on top of urban infrastructure. The vegetated rooftops are appreciated by many interest groups, as they often provide a beautiful park or recreation area in sterile developed urban area. “Even in densely populated areas, birds, bees, butterflies and other insects can be attracted to green roofs and gardens up to 20 stories high” [The London Ecology Unit, 1993].

A green roof meets LID expectations, as they efficiently capture and temporarily store urban stormwater runoff; which helps to maintain the pre-development peak discharge rate. Generally runoff interception can vary from 15-90% based on soil depth, and rainfall intensity [USEPA, 2000]. Figure 2.3 shows the ability of a vegetated rooftop with a 3.35-inch soil thickness to reduce runoff during a 24 hour storm event [Roof Scapes, Inc., 2000]. In addition to their ability to retain stormwater runoff, vegetated roofs can also reduce the urban heat island effect by increasing evapotranspiration and providing shade [Bass, 1999]. Although these urban retrofits are aesthetically pleasing, this LID technology does not incorporate a media layer to achieve TN removal.

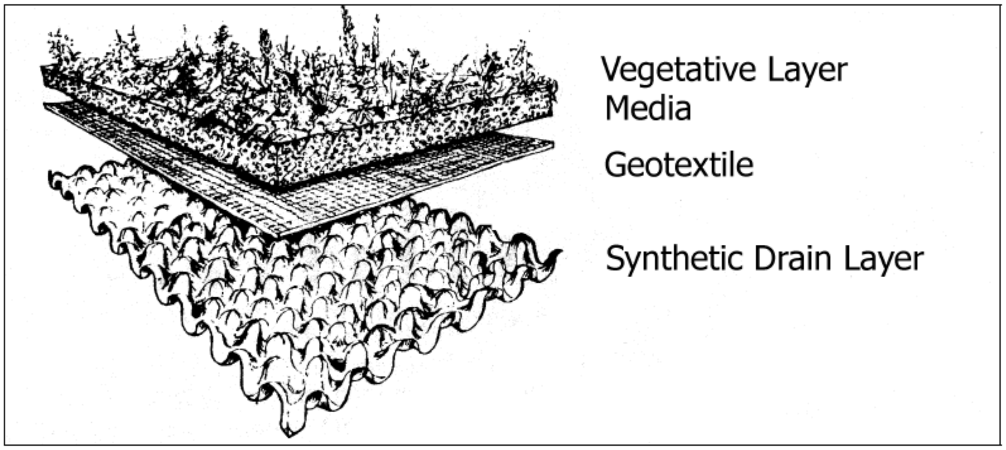

Figure 2.2. Depiction of the different layers found in a typical vegetated rooftop [USEPA, 2010].

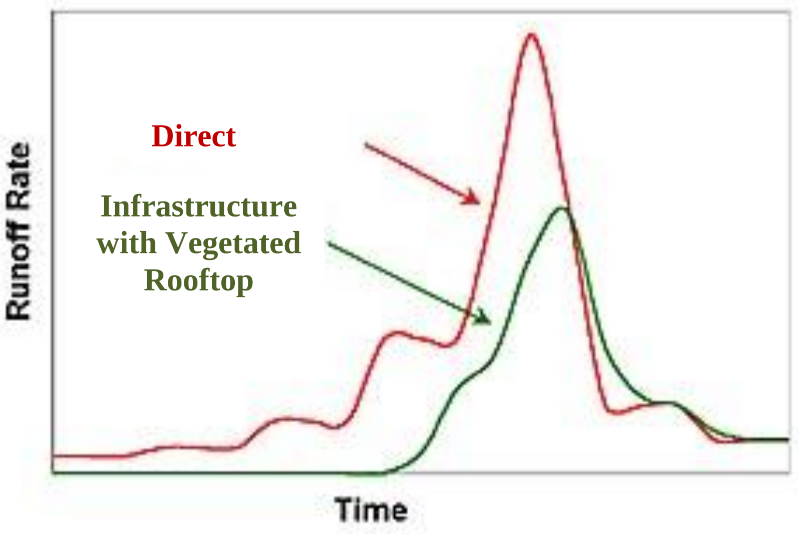

Figure 2.3. Stormwater runoff from a 3.35-inch green roof, during a 24-hour rainfall event [Roofscapes, Inc., 2000].

Permeable pavement is a LID technology that replaces non-pervious urban roadways and sidewalks with pervious surfaces; where stormwater runoff can then infiltrate more readily. A traditional, non-pervious urban pavement system contributes to flooding and pollution issues associated with non-point source pollutant contamination. Stormwater runoff permeates through the porous pavement into the underlying gravel/stone layer. The underlying layer acts as a filter, cleaning out the pollutants [USEPA, 2000]. There are a many urban areas utilizing this new technology, including SWFL [Sarasota County, 2009]. However, overall construction costs must consider maintenance issues, as the permeable surfaces are prone to clogging [USEPA, 2000]. There are several different types of pervious pavements, which include: (1) Plastic pavers: A plastic honeycomb grid in which grass or other vegetation can grow; (2) Concrete pavers: Concrete blocks with spacers in between them (for better drainage) and; (3) Asphalt/concrete: Fine particles are left out, to improve porosity [Bean et al., 2004].

Rain barrels are an excellent LID technology, as they are easily installed and relatively cheap; therefore making them affordable for private homeowners. Rain barrels are large contains that attach to roof gutters (Figure 2.4). A traditional home is equipped with rain gutters, which are designed to concentrate stormwater runoff to designate outlets; therefore reducing the flooding around a residential home (for example). “A typical 1/2-inch rainfall will fill a 50- to 55- gallon barrel” [SWFWMD, 2010]. “A 2,000-square-foot roof can collect about 1,000 gallons of water per year (accounting for about a 20% loss from evaporation, runoff and splash)” [SWFWMD, 2010].

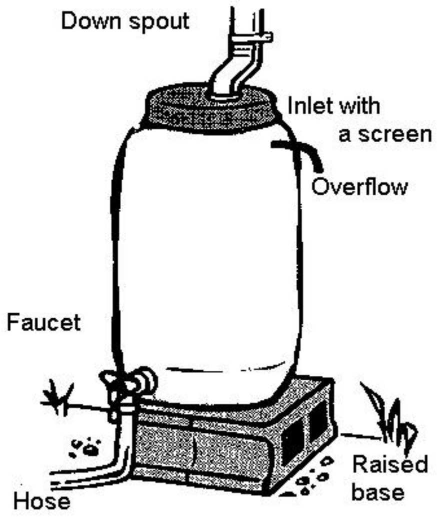

Figure 2.4. Typical rain barrel setup, to collect stormwater runoff from a rooftop [source: http://www.ci.berkeley.ca.us]

Rainwater harvesting practices have been used to capture stormwater used for drinking water since the Bronze Age (2000-1200 B.C.) [Hunt, 1999]. Today many developing nations still collect rainwater for drinking water purposes. However, in the developing country the improper treatment of rainwater would only be used for non-potable (non-drinkable) water uses [Hunt, 1999]. Some common uses for the non-potable rainwater collected in a rain barrel include: irrigating lawns and landscapes, flushing toilets and washing vehicles [Hunt, 1999]. Often rain barrels are incorporated into a larger LID system; where a vegetated roof will filter stormwater, which would collect in a rain barrel, and then possibly into a bioretention cell. Because of its low cost, many homeowners in SW Florida are utilizing these LID technologies to reduce irrigation costs, and to maintain landscapes during seasonal droughts [CUES, 2006].

Detention systems have been utilized in urban areas for many years, to control flooding from stormwater runoff [University of Wisconsin, 2005]. More recently, LID has employed the use of a detention system that incorporates a defined media configuration, to achieve enhanced nutrient reductions [USEPA, 1999]. The bioretention system, or rain garden, is configured with vertical layers of media that are able to achieve different steps in the nutrient removal process. Figure 2.5 illustrates the conventional bioretention cell configuration used to treat stormwater runoff.

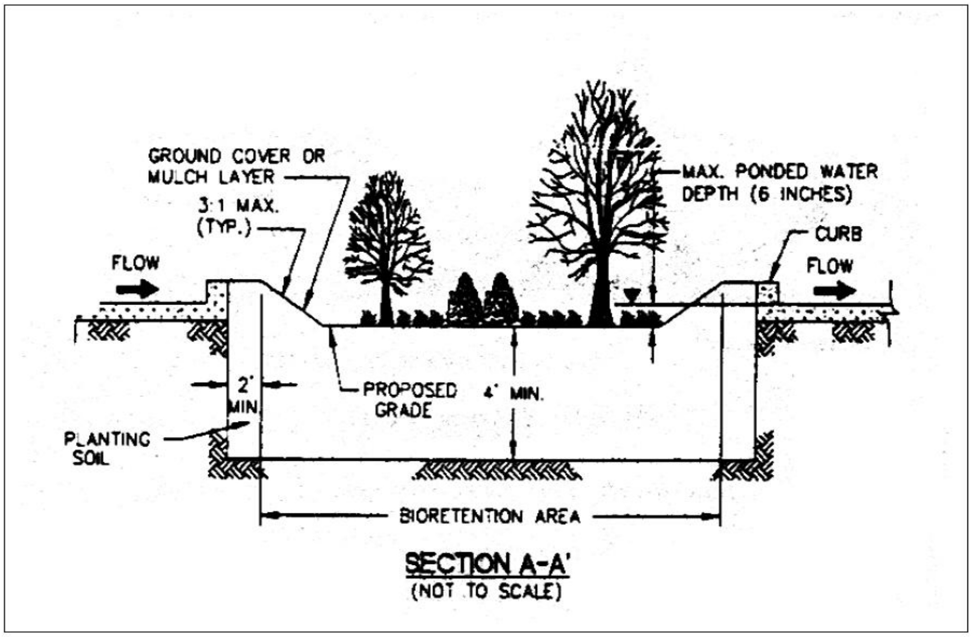

Figure 2.5. Typical bioretention system [Prince George's County DEP, 1993].

Bioretention cells are considered a LID because the stormwater runoff flows through the six components, where the various mechanisms are able to restore pre-development, hydrologic flows. However, the most notable feature of these systems is their ability to significantly reduce nutrients like nitrogen and phosphorus, petroleum-based pollutants, sediments, and organic matter. Prince George's County Department of Environmental Resources (PGCDER) reported that both total suspended solids (TSS) and organic matter were reduced by 90% when utilizing a bioretention cell [PGCDER, 1993]. Recent research by Davis et al. [2001] showed a significant reduction in heavy-metal contaminants (>92% for lead, copper and zinc), as well as for TP (80% reduction) and ammonia (60-80% reduction). However, Davis et al. [2001] only saw nitrite + nitrate-nitrogen (NO_3^--N) reductions of around 24%.

In a conventional bioretention system, a ponding area attenuates peak flows, and then water slowly infiltrates through vegetated soil, mulch and sand layers to the natural groundwater. Figure 2.6 shows a cross-sectional depiction of a conventional bioretention cell. The surface layer of a bioretention cell is generally planted with vegetation such as flowering plants and shrubs, to provide an aesthetic, landscaped area. Treatment of stormwater runoff is achieved through evapotranspiration, plant uptake, biodegradation, filtration and adsorption [USEPA, 1999].

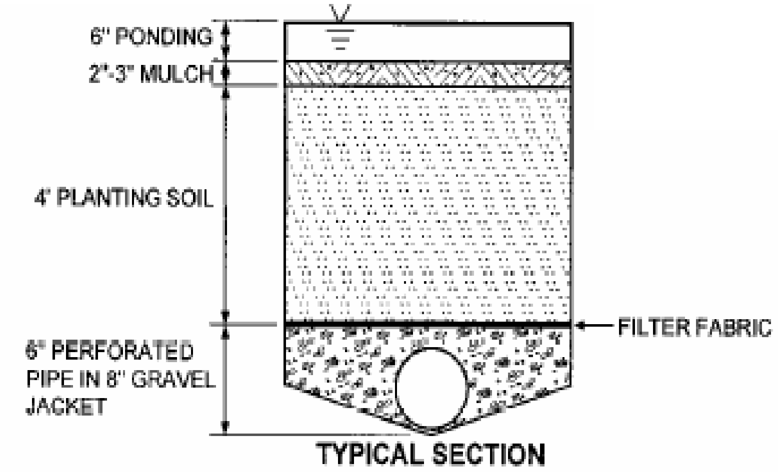

Figure 2.6. Schematic of a conventional bioretention cell [MDE, 2000].

An alternative bioretention system design was proposed by Kim et al. [2003], which resulted in significant removal efficiencies for total nitrogen. In this system, runoff gradually infiltrates through a sand layer, where nitrification occurs. The nitrified stormwater is then conveyed through a submerged (anoxic) denitrification region, which is supplied with an electron donor (e.g. wood chips as a carbon source), where nitrate is reduced to nitrogen gas by anoxic heterotrophic bacteria. The outlet is configured so that the denitrification zone remains submerged to maintain the anaerobic conditions required by the denitrifying organisms. Figure 2.7 shows a cross-sectional illustration of an alternative bioretention cell designed to achieve total nitrogen removal (the nitrification occurs in aerobic sand layer and the denitrification in the submerged, anaerobic wood chip layer) [adapted from Ergas et al. 2010].

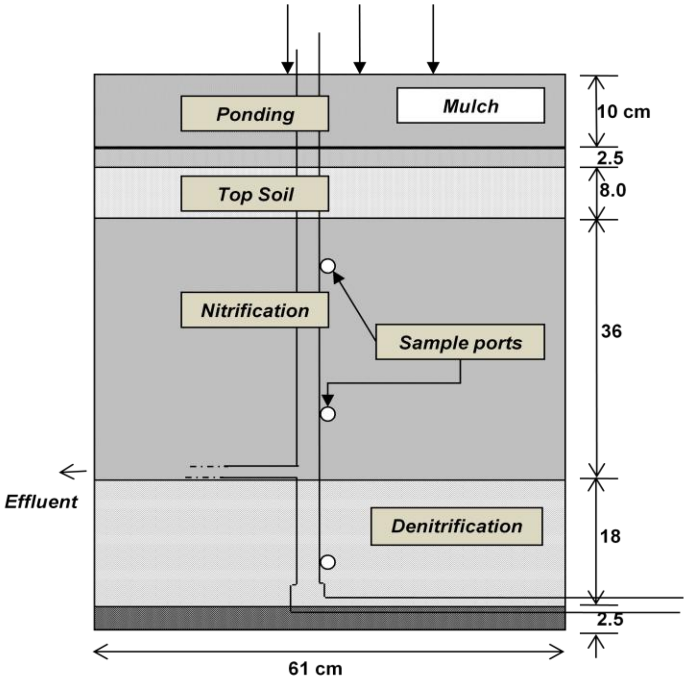

Figure 2.7. Schematic of an alternative bioretention cell for treatment of nitrate rich stormwater [Ergas et al. 2010].

Recently, Ergas et al. [2010] published results from a pilot-scale study using the aforementioned nitrogen-removing bioretention system design. This study investigated treatment of typical urban stormwater under controlled laboratory conditions followed by two years of field studies with agricultural runoff. Results from this study showed high total nitrogen removal efficiencies (>80%) when using wood chips as the denitrifying media source. Additionally, this design achieved good overall average removal efficiencies for COD (55%), BOD_5 (69%), suspended solids (81%), total P (54%), and PO_4^{3-} (48%) [Ergas et al., 2010].

The results of prior studies have shown that the use of this alternative bioretention cell design can increase nitrogen removal, when compared to a typical bioretention cell configuration. The incorporation of wood chips into bioretention media is effective in removing nutrients from stormwater runoff. No controlled studies have been done comparing the different designs and media materials under field conditions in SW Florida, however. This is particularly important in Southwest Florida due to high rainfall and water table level variations in the region. In addition, little data are available on the maintenance requirements and long-term performance of these systems.

Environmental Considerations for Implementing LID in SWFL

To better understand the ability to effectively introduce bioretention cells to treat stormwater runoff in SWFL it is first necessary to understand the dynamics of the local hydrologic system. One main purpose for incorporating bioretention cells in SWFL is to achieve groundwater recharge; therefore, it is necessary to thoroughly understand the factors that influence the interaction between surface and groundwater, in the watershed [Kish et al. 2007]. The purpose of this section will be to discuss the regional climate, including the rainfall characteristics in Sarasota County. This section will then address the geographic characteristics of Sarasota County; including the hydrogeology, the watershed characteristics and the water use within Sarasota County.

A watershed is an area of land where all the groundwater and surface water drains into the same water body [USEPA, 2009]. Sarasota County consists of six major watersheds- Sarasota Bay, Little Sarasota Bay, Myakka River, Dona/Roberts Bay, Roberts Bay and Lemon Bay- this project will focus specifically on the Lemon Bay watershed (Figure 2.8). In July, 1986 the Florida Legislature designated Lemon Bay as an aquatic preserve [Florida DEP, 2011]. At least 230 species of fish depend directly on the mangroves and aquatic ecosystem of Lemon Bay. Lemon Bay is also home to endangered species, like the manatee and sea turtle, which come to feed on the nearshore seagrasses [Florida DEP, 2011]. The Lemon Bay watershed contains a series of creeks; this project will focus specifically on the creek known as Alligator Creek, which can be seen in detail in Figure 2.8. Alligator Creek is approximately four miles long, and drains into the northern tip of Lemon Bay [Sarasota County Wateratlas, 2010].

A hydrologic cycle is a complex system that links climate, geography, soils, hydrogeology, land cover, land use, and urbanization of a certain area, or watershed [Kish et al. 2007]. The specific hydrologic system for the Lemon Bay watershed is linked to the unique environmental setting of the area. According to Sarasota County’s LID Manual, LID technologies should be designed to mimic the natural hydrologic flows of a proposed site [Sarasota County, 2009].

Southwest Florida is well known for its long, warm, humid summers and short, mild, dry winters; these characteristics follow a somewhat predictable seasonal pattern [Kish et al. 2007]. Typically, in the winter months (December through February) the average temperature ranges from forty-eight degrees Fahrenheit in the evening hours, and reach up to seventy-one degrees Fahrenheit in the day time; the summer months (June-August) will typically see temperatures ranging from seventy-two degrees Fahrenheit to ninety-one degrees Fahrenheit [Soil Conservation Service, 1991].

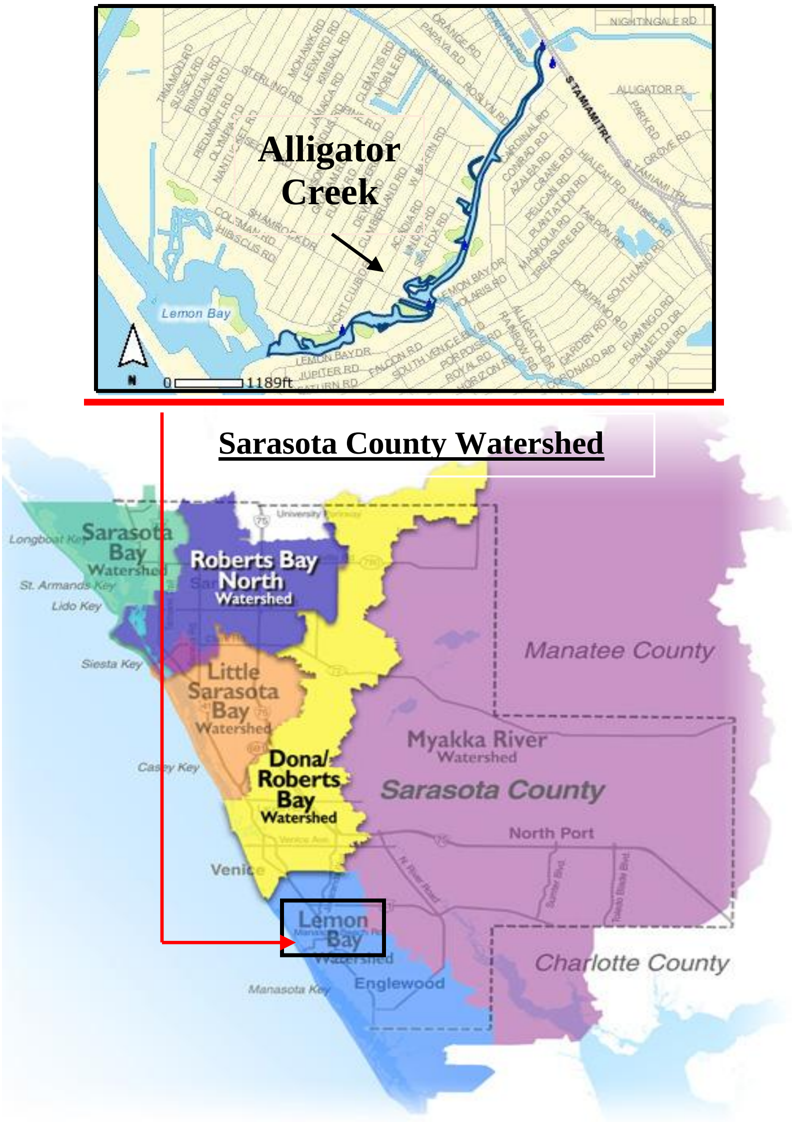

Figure 2.8. Detailed map of Alligator Creek, located within the Lemon Bay watershed [Sarasota County Wateratlas, 2010].

Seasonal variations are seen in rainfall patterns in SWFL as well, but precipitation events will often occur in somewhat predictable patterns; winter storms are mostly formed by cold fronts moving south across the northern US, whereas tropical storms will generally move northward across Florida, from the Atlantic, and local thunderstorms will develop almost daily in the summer months [Kish et al., 2007]. Although these storms seem somewhat predictable, the actual precipitation that any one storm event will produce, locally, varies substantially. Historical rainfall trends for Sarasota County show that rain events will occur almost daily in the rainy period, from July through October; however, in the dry period (November through June) rain events are sparse [SWFWMD, 2005].

The purpose of using an LID technology is to achieve predevelopment hydrologic functioning of a site; therefore it is essential that this paper address the hydrogeology of this region, in order to better understand the potential to implement this technology across SWFL. This region is well known for its sandy soils. Florida was once at the bottom of the ocean; therefore leading to topography consisting of a series of relict marine terraces [Campbell, 1985]. Specifically, five hydrologic soil groups exist within Sarasota County, as defined by the National Resource Conservation Service (NRCS): (1) Types A (well-drained), B/D (moderately well-drained when dry, somewhat poorly drained when wet), C (somewhat poorly drained), C/D (somewhat poorly drained when dry, poorly drained when wet), and D (poorly drained) [Sarasota County, 2009]. Most soils are classified in the B/D hydrologic soil group, due to a high water table [Sarasota County, 2009]; therefore, making them poorly drained and consisting of mucky, sandy or loamy soils [Kish et al., 2007].

Soil characteristics play an important role in the hydrology of a watershed. Poorly drained soils will lead to an increase in stormwater runoff, nutrient transport, and in increase in depressional storage of water into nearby retention basins [Soil Conservation Service, 1991]. According to the US Geological Survey's Websoil Survey, the proposed site for the bioretention retrofit project consists of mostly Myakka fine sands (specifics of this particular site and soil composition will be discussed in more detail in Chapter four of this paper), which is classified as type B/D (moderately to poorly drained) soil. Therefore, according to NRCS, during the wet weather season when the soil is saturated, there will be in increase in stormwater runoff entering retention basins; however, in the dry weather season, stormwater would percolate more readily into underlying groundwater reservoirs. The hydrologic path taken by the stormwater would depend on the precipitation duration and the depth to the underlying groundwater [Kish et al., 2007].

Groundwater is one of Florida's most valuable resources, as nearly 80% of the 1 billion gallons of water used daily by residents comes from the Upper Floridian Aquifer [SWFWMD, 2001]. An aquifer is the term used to describe the location of the groundwater. The three aquifers underlying Sarasota County, in ascending order, are the Upper Floridian Aquifer, the intermediate aquifer system and the surficial aquifer system [Barr, 1996]. The average depth to the surficial aquifer system in this region is generally less than five feet (1.5 m) [Kish et al., 2007]. The depth to the surficial aquifer can vary seasonally by as much as five feet (1.5 m) [Kist et al., 2007]; therefore, infiltration-dependent LID-technologies will be constrained under wet weather conditions in this area [Sarasota County, 2009].

Implementation of LID Technologies in Southwest Florida

The implementation of LID technology in Florida has been slow moving; as little research is available to justify the effectiveness of these BMPs in SWFL. As previously discussed, SWFL has very different hydrologic and geologic characteristics when compared with the northwestern US; where successful implementation of LID technologies originated. However, some LID projects were recently completed in Sarasota, Dunedin and Hillsborough Counties. Table 2.2 provides an overview of different types of LID projects that have recently been completed in southwest Florida, as well as some background information for each project.

Of the six LID projects recently finished in SW Florida, only the Florida Aquarium performed post-development nutrient analyses in order to justify the benefit of utilizing LID in SW Florida. The USEPA [2000] released a literature review, which summarized the results of the yearlong study conducted at the Florida Aquarium, from 1998-1999. The project was designed in an effort to detain all stormwater runoff onsite, instead of allowing it to flood streets or flow into sewer systems and out into the Tampa Bay. The entire 4.65 ha parking lot was used in this study to define the drainage basin [USEPA, 2000]. Each parking space within the entire parking lot was shortened, to allow enough space to retrofit a grassed swale between each row. Figure 2.9 shows a diagram of the Florida Aquarium parking lot that was retrofitted with the bioretention cells and permeable pavement in this project.

The study area for this project consisted of four separate scenarios, with a total of eight basins (two basins for each of the four scenarios), and each configuration was equipped with the appropriate analytical tools for collecting and monitoring stormwater runoff. The first scenario was asphalt paving with no swale; the second included a swale; the third scenario was traditional cement paving with a swale and; the final scenario looked at permeable pavement with a connected swale. The results of this study highlight that the poorest performance was seen with the asphalt with swale scenario [USEPA, 2000].

Table 2.1. Summary of LID projects in southwest Florida.

Type(s) of LID Technology	Project Name	Project Location	Project Overview
Pervious Pavement & Grassed Swales	The Florida Aquarium	Hillsborough County	Permeable pavement laid for parking lot of facility, with stormwater runoff being piped underground to grassed swales
Detention with Biofiltration	Clark Station	Sarasota County	Bioretention pond added to existing BMP's for enhanced nutrient reduction
Permeable Pavers	Reid Habitat for Humanity	Sarasota County	Limit fill required to grade pre-developed land, and use permeable pavers designed to achieve 85% load reductions
Stormwater Harvesting	The Bridges	Sarasota County	Use of existing ponds for stormwater harvesting and irrigation purposes
Cistern/Large Rain Barrel & Green Roof	South Lido Beach Park Restroom Pavilion	Sarasota County	Cistern provides non-potable water for toilet flushing and green roof proposed to achieve a 75% load & nutrient reduction
Pervious Pavement	Dunedin Community Center	Pinehurst Rd. Dunedin, FL	Grassed parking lot; reinforced with "Geo-Web"

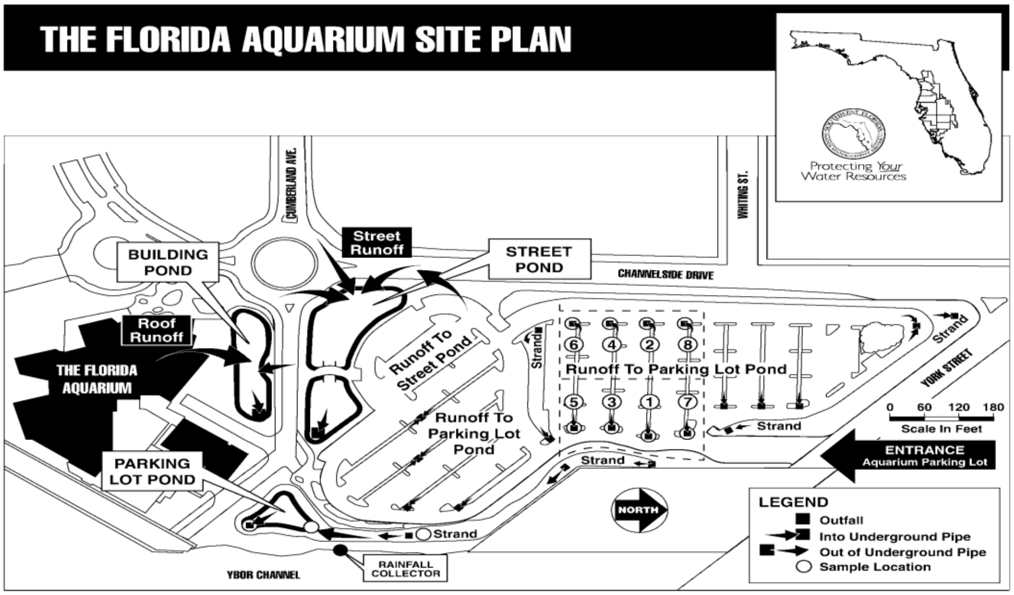

Figure 2.9. Florida Aquarium project depiction [Rushton, 1999].

Modeling an Alternative Bioretention System

Although some studies have modeled the hydraulic performance of bioretention systems [Lucas, 2010; Heasom et al., 2006; Abi Aad et al., 2010], presently there are no studies that have modeled the efficiency of these alternative bioretention systems to achieve denitrification. Considering that denitrifying bioretention systems are a relatively new advancement in bioretention system design, it was not surprising that there is not more literature on the ability to model nitrogen reductions in these systems. EPA's SWMM-5 is capable of modeling low impact development technologies, yet it is not capable of modeling an alternative (denitrifying) bioretention system. Therefore, a more in-depth design was needed, in order to illustrate a multi-layered, alternative bioretention system.

A case study analysis was performed, in order to determine the estimated nitrate reductions of the proposed redesigned bioretention cells at the Venice, FL site using SWMM-5 to simulate post-development annual nitrogen loading rates. The research for this project was carried out in a four phase research process. The objective of Phase I was to define site-specific input parameters of the proposed case study site where Sarasota County will develop a series of bioretention cells in Venice, FL. The objective of Phase II was to estimate the rate loss coefficient values (k_1 and k_2) for nitrification and denitrification. The objectives of Phases III and IV of this project were to develop a SWMM-5 model of an alternative (denitrifying) bioretention system, to evaluate the hydrologic performance and estimate nitrogen removal efficiencies.

State and Local Regulations

The proposed site for the bioretention cell retrofit project discussed in the paper is located in the city of Venice; which is in Sarasota County, FL. Sarasota County's *Land Development Regulations,* Article I Sec. 74-4, requires development projects to provide "adequate stormwater management [so as] to reduce the impact of flooding to a minimum" and "protection of Sarasota County's natural systems and scenic resources, including the quality of air and both surface and groundwaters and the preservation of their ecological integrity" [Sarasota County, 2009]. LID is an effective tool which can be used to reduce flooding and non-point source pollution, while meeting these County land-development standards [Sarasota County, 2009].

Chapter 62-40.432 of the Florida Administrative Code (F.A.C.) defines the water quality regulations in the State of Florida. Based upon the language outlined in this chapter, all stormwater management systems designed within the State of Florida must "achieve at least 80% reduction of the annual average load of pollutants that would cause or contribute to violations of state water quality standards" (per Chapter 62-40.432 F.A.C.). New stormwater best management practices must address these regulations, and be designed according to the guidelines established by this rule; then, presumably discharge from these stormwater systems will meet state regulatory standards [Harper and Baker, 2007]. According to SWFWMD, post-development nutrient characteristics must meet, or be better than the pre-development characteristics. In order for a stormwater development project to qualify for a NPDES permit, planners and/or engineers must provide justified evidence that the post-development nutrient characteristics will meet the State's rule requirements [SWFWMD, 2010].

Chapter Three:

SWMM-5 Capabilities

This chapter will discuss the purpose for incorporating the SWMM-5 model, the SWMM-5 model framework and model inputs based on site -specific parameters, and how the software quantifies hydrologic flows and total nitrogen removal.

SWMM-5 Software

The first Storm Water Management Model (SWMM) software was developed in the early 1970's, and has undergone various transformations since its creation [USEPA, 2010]. The SWMM software can simulate a single precipitation event or provide long-term simulations of water quality and quantity for a user defined drainage basin [USEPA, 2010]. The original SWMM software was not capable of addressing methods for layered biofiltration systems [Lucas, 2010]. The latest version of the SWMM software, (SWMM 5.0.021) "operates on a collection of subcatchment areas (and now LID/BMP areas) that receive precipitation and generate runoff and pollutant loads after simulation evaporation and infiltration losses from the drainage basin" [USEPA, 2010]. This section will compare different approaches to simulating nutrient treatment, compare the capabilities of the latest SWMM software, and provide details on the various components of SWMM-5 and their uses.

The EPA SWMM-5 software is free, downloadable software provided by the USEPA (at http://www.epa.gov/ednnrmr/models/swmm/index.html). The benefit of using the SWMM-5 software for this project is its ability to compare the pre- vs. post-development hydrologic model outputs. Comparing the pre- vs. post-development results allows engineers and planners to make better decisions about the hydrologic impact on planned development areas [Jang et al., 2007].

SWMM-5 was designed to account for the various hydrologic processes that can differ at each site, including; "time-varying rainfall, rainfall interception from depression storage, infiltration of rainfall into unsaturated soils, percolation of rainwater into groundwater layers, interflow between groundwater and the drainage system, nonlinear reservoir routing of overland flow and runoff reduction via LID components" [USEPA, 2010]. The subcatchment properties for a bioretention cell in the SWMM-5 model are listed in Table 3.1.

Table 3.1. General subcatchment characteristics as defined in SWMM-5 [adapted from Abi Aad et al. 2010].

Subcatchment Properties	**Input Values**
Area	Area of the subcatchment; it depends on the availability of land on the parcel
Width	Characteristic width of flow running over the subcatchment
Slope	Percent slope of the water surface flowing over the subcatchment
Imperviousness	Percent of impervious area
Impervious *N*	Manning's factor *n* for the impervious portion of the subcatchment
Pervious *N*	Manning's factor *n* for the pervious portion of the subcatchment
Dstore-imperv	Depth of depression storage on the impervious area (in.)
Dstore-perv	Storage depression over the pervious portion of the subcatchment
% zero-imperv	Percent of the impervious area with no depression storage
Outlet	Defines the node receiving the flow

SWMM-5 Compartments

"There are four major categories to conceptualize a drainage system as water and material flows between environmental compartments that the SWMM5 model addresses: the atmospheric compartment, the land surface compartment, the groundwater compartment and the transport compartment" [USEPA, 2010]. Not all compartments must be considered for every model [USEPA, 2010]. The atmospheric compartment addresses rainwater and nutrient inputs, which is represented as a rain gauge. The land surface compartment (subcatchment) addresses the pervious receiving area and the outflow leaving this area. One or more subcatchments can be used to represent different drainage areas. There is also a groundwater compartment, which was not used to develop the model in this study. The transport compartment includes orifices. Orifices were used to control flow into the storage unit nodes in the model developed for this case study. More details about the different compartments used to develop the model in this study are listed in the following subsections.

Atmospheric Compartment

Rain gauges are used to supply one or more subcatchments with precipitation data. Multiple rain gauges can be incorporated into a SWMM-5 model, in order to evaluate single-event storms. The rain gauge used for this model is a user-defined time series. Specific details regarding the rainwater data are presented in Chapter 6.

Land/Subcatchment Compartment

Subcatchments in the SWMM-5 model represent the hydrologic flow of stormwater runoff across a defined drainage area. A single subcatchment was used to represent the drainage basin; draining into the thirteen bioretention cells along Venice

East Blvd., for this case study. The breakdown of nitrogen is represented using a system of nodes (a node is defined in more detail below).

A subcatchment can drain into another subcatchment, or into a defined node. There are four different types of nodes that can be used to model drainage systems in SWMM5: junctions, outfalls, dividers and storage units. A storage unit node was used for this model; reasons for choosing to use a storage unit node will be discussed in the following subsection. As previously discussed, a subcatchment can be subdivided into permeable and impermeable subareas. "Impermeable subareas within a subcatchment can be further divided into two subareas- one with depression storage and/or one without" [USEPA, 2010]. The stormwater runoff from the impervious drainage area was routed to drain to a storage unit node for the model developed in this study.

Storage Unit

A storage unit node was selected for the development of the model in this study, to represent the different layers within a bioretention cell. The storage unit node is a good object to use for this study, because it allows for treatment within each node. Therefore, each layer can account for a different process within the alternative bioretention cell by inputting treatment expression specific to the nitrification and denitrification processes (treatment expressions are discussed in detail in the subsequent section). The principle input parameters for the storage nodes used for this project are shown in Table 3.2.

Table 3.2. Principle input parameters needed to calibrate the SWMM-5 model for this case study. [Adapted from USEPA, 2010]

Storage Unit Node: Input Parameters
Invert Elevation
Maximum Depth
Ponded Area
Treatment
Infiltration
Storage Curve

Computational Capabilities

“The precipitation flowing to the permeable subarea of a subcatchment into the unsaturated upper soil layer can be incorporated into simulations run in SWMM-5 using three different methods: the Horton infiltration method, the Green-Ampt method and the Curve Number infiltration method” [USEPA, 2010]. The variations between each infiltration method and the method that was selected for the model designed in this study are described below.

Horton Infiltration Method

Horton’s Equation is used to describe groundwater infiltration rates or volumes [Dickenson, 2008]. The equation “represents an empirical formula, where the rate at which water percolates through the soil surface is constant and then begins to decrease over time” [Dickenson, 2008]. The percolation rate eventually levels off when the soil saturation level reaches a fixed value. Horton’s equation can also be used to calculate the total volume of infiltration after a period of time. The input SWMM-5 parameters for this method include the “maximum and minimum infiltration rates, a decay coefficient which describes how fast the rate decreases over time, and the time it takes a fully saturated soil to dry” [USEPA, 2010].

Curve Number Infiltration Method

The curve number method (CN method), also termed the runoff curve number (RCN), is an empirical formula developed by the USDA. The CN method is used in hydrologic calculations to determine the amount of runoff or direct infiltration of runoff from a storm event [USDA, 1986]. The runoff curve number is based on hydrology, soil conditions, land use and treatment. “The input parameters for this method are the CN and the time it takes a fully saturated soil to dry completely” [USEPA, 2010].

Green-Ampt Infiltration Method

In this work, the Green-Ampt method [Green and Ampt, 1911] was selected for modeling infiltration. The Green-Ampt equation is a “semi-theoretical formula”, which was used most often, in comparable studies, when modeling bioretention cells [Lucas, 2010; Tsihrintzis and Hamid, 1998; Abi Aad et al., 2010]; as the Green-Ampt method is “well suited for predicting surface runoff from the pervious” area of a bioretention cell during a storm event [Heasom et al., 2010]. Before a storm event the soil moisture content is assumed to be able to sufficiently able to handle infiltration. During a storm event the stormwater will flow through the spaces between the soil particles, creating a wetting front. “Gravity, the matrix potential of the dryer soil underneath, and Darcy’s Law are all important factors in the downward flow of the stormwater into the underlying soil layer” [Heasom et al., 2010].

Modeling Treatment with SWMM-5

The SWMM5 software is also capable of predicting the reduction of pollutants through treatment in storage units, by analyzing the buildup, washoff, transport and treatment of any number of constituents. The ability to model the removal of pollutants was the key factor in selecting the SWMM5 model for this research. Within the model, removal of pollutants can be dependent on co-pollutants. For example, in the model developed in this project NO_3^- was considered a co-pollutant, as the concentration following into the denitrification layer was dependent on the concentration of the reacted NH_4^+ exiting the nitrification layer. “Treatment can be modeled by using treatment functions within a node, and mathematical expressions for computational purposes” [USEPA, 2010]. For purposes related to the model developed for this research, the pollutant removal was expressed as a concentration (C). The equations derived for the SWMM-5 model developed in this project are presented in Chapter 5.

LID Components

SWMM-5 is capable of modeling LID, including: bioretention cells, infiltration trenches, porous pavement, rain barrels and vegetative swales [USEPA, 2010]. This project was specifically interested in the capability of SWMM-5 to model the efficiency to achieve denitrification in an alternative (denitrifying) bioretention system. “Because the LID controls cannot act in series”, SWMM5 is not capable of modeling the capability of LID controls to achieve denitrification [USEPA, 2010]. Therefore, the model designed for this project quantifies treatment within a bioretention system by using a network of storage units (where each storage unit represents a different treatment layer in an alternative bioretention cell); each with its own treatment capabilities. More details on the conceptual framework, including a diagram of how runoff flows through the system, can be seen in Chapter 6.

Chapter Four:

Site Characteristics

The overall goal of this research project was to investigate the performance of a proposed bioretention system in Venice, FL to treat non-point sources of nitrogen from stormwater runoff. Phase I of this project was to determine the hydrologic and quality characteristics of the pre- developed bioretention retrofit site in Venice, FL. This chapter includes a description of the site, including runoff and physical characteristics based on the literature, as well as information on the proposed bioretention system. Site-specific nutrient characteristics analyzed during Phase I of this project are discussed in Chapter 5.

Physical Characteristics

The site for the proposed bioretention cell retrofit project (Figure 4.1) is located on Venice East Blvd. in the City of Venice, FL. This area is coded as a single-family residential community, as defined by the Florida Land Use Code and Classification System. The four-laned road is curbed, with storm sewers that drain into a retention basin that runs perpendicular to Venice East Blvd. This retention basin empties out into Alligator Creek, and then into Lemon Bay. The purpose of the retrofit project is to significantly reduce the nutrient loading to Alligator Creek, an impaired water body, by reducing the nitrogen concentration in the stormwater runoff. This will be achieved by increasing the pervious area to allow an increase in groundwater infiltration. The proposed project includes cutting the curbed gutter at specified locations, to allow some of the stormwater runoff to be redirected into a series of bioretention cells. Figure 4.1 shows the location of one of the thirteen cells.

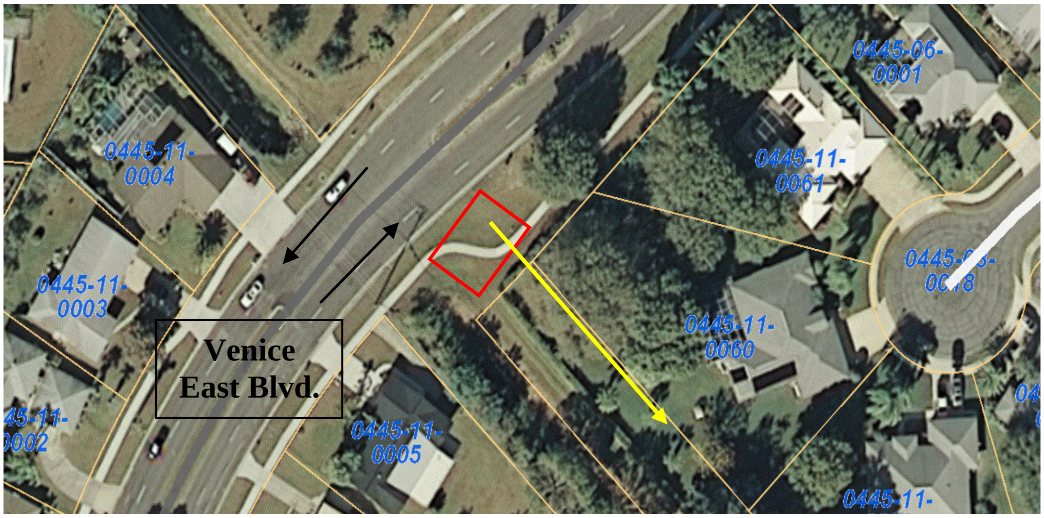

Figure 4.1. Proposed location of cell thirteen, one of 13 bioretention cells planned (outlined in red). This cell will be the terminal end of the site, and will drain into a drainage ditch (highlighted in yellow) that runs perpendicular to Venice East Blvd.; with runoff will move away from Venice East Blvd. towards a retention pond, that eventually empties into Alligator Creek.

The subcatchment (contributing area) begins at Center Road in Venice, FL. Venice East Blvd., and runs perpendicular to Center Road (Figure 4.1). Venice East Blvd is designed so that runoff will flow toward the curb of the road. The road was designed so that the center of the road is at higher elevation than the curbed area. Additionally, Venice East Blvd. is sloped so that runoff flows from Center Road to the terminal end of the subcatchment, which is designated as the stormwater drainage ditch. The approximate length of the retrofit site is two miles. The system was designed by Sarasota County, with plans to cut the curb at various locations along Venice East Blvd. These curb cuts will provide both an inlet into each of the cells and an outlet in case the system overflows during heavy rain events. Site-specific input parameters and hydrologic characteristics are presented in Chapter 5.

Proposed Bioretention System Design

The system of thirteen cells was designed by Sarasota County with no connections between each of the thirteen cells. Each cell is designed as a closed system (i.e., effluent from one cell will not influence flows or nitrogen loads into the next cell). The system of cells is designed so that all impervious flows will be routed toward the bioretention cells. The impervious area at the Venice East Blvd. bioretention site accounts for approximately 41.8 % of the total area.

Sarasota County provided plans for cell number 13; one of thirteen proposed cells at the Venice East Blvd. site. All 13 cells were assumed to be of equal size. Cell 13 is approximately 23.4 m long by 9.14 m wide (76.7 ft by 30.0 ft). Therefore, the total area for all thirteen cells is approximately 2,780 m^2 (29,900 ft^2). The media begins approximately 86.4 cm (34 inches) below the existing grade, with the top of the media at approximately 55.9 cm (22 inches) below the lip of the bioretention cell.

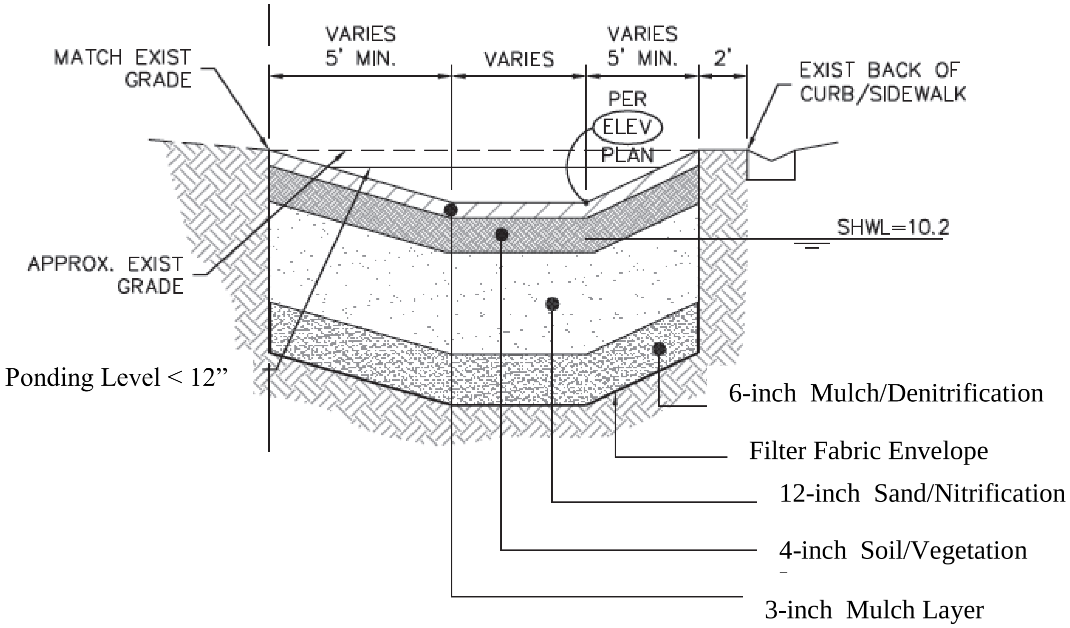

Figure 4.2. Site plan of bioretention cell 13 [plans provided by Sarasota County].

Runoff Characteristics

Table 4.1 presents typical constituents analyzed in stormwater runoff, the analytical methods used, the method detection limits for each constituent, and the typical concentration of each constituent in stormwater runoff in Florida based on the literature. Many of these same constituents were analyzed during Phase I of the model development, as discussed in Chapter 5.

Table 4.1. Analytical methods summary and typical nutrient concentrations.

Analyte	**Analytical Method**	**Method Detection Limit**	**Typical Conc. in Stormwater Runoff based on Literature**
Total Nitrogen (TN)	HACH Test 'N Tube: Persulfate Digestion Method	0.5 mg/L as N	1.17 mg/L [for a grassed swale in Sarasota County ERD (2004)]
Ammonium (NH_4^+-N)	APHA et al. Standard Method 4500-NH_3 D	0.06 mg/L as N	0.17 mg/L [Dillon & Chanton, 2005]
Total Kjeldahl Nitrogen (TKN)	APHA et al. Standard Method 351.2	0.594 mg/L	1.55 mg/L [PBS&J, 2010]
Ammonia (NH_3-N)	APHA et al. Standard Method 4500-NH_3 C	0.005 mg/L	0.31 mg/L [PBS&J, 2010]
Nitrate + Nitrite as Nitrogen	APHA et al. Standard Method 353.2	0.005 mg/L as N	0.42 mg/L [(nitrate-nitrite combined) PBS&J, 2010]
Org N	Calculated by Difference*	N/A	1.38 [PBS&J, 2010]
Ortho-Phosphorus as P	APHA et al. Standard Method 365.3	0.002 mg/L	0.34 mg/L [PBS&J, 2010]
Total Phosphorus (TP)	HACH Test 'N Tube: APHA et al. (2005) SM4500-P E	0.02 mg/L as P	0.506 mg/L [for a grassed swale in Sarasota County ERD (2004)]
5-day Biochemical Oxygen Demand (BOD_5)	APHA et al. (2005) Standard Method 5210B: 5-Day BOD Test	0.5 mg/L	4.4 mg/L [for a grassed swale in Sarasota County ERD (2004)]
Alkalinity	APHA et al. (2005) Standard Method 2320B: Titration Method	0.67 mg/L as $CaCO_3$	20.91 mg/L [(North Florida stormwater) H. Zhang, 2010]
Total Suspended Solids (TSS)	APHA et al. (2005) Standard Method 2540D	0.57 mg/L	10.1 mg/L [for grassed swale in Sarasota County ERD (2004)]
Volatile Suspended Solids (VSS)	APHA et al. (2005) Standard Method 2540E	0.57 mg/L	N/A
Total Coliform Units (CFU)	APHA et al. (2005) 9222B: Membrane Filtration Test	20 CFUs per plate required to assume validity	N/A
Dissolved Oxygen (DO)	APHA et al. (2005) Standard Method 4500H	1.01 mg/L	N/A
pH	APHA et al. (2005) Standard Method 4500H	0-14 pH units	7.78 [(N. Florida stormwater) H. Zhang, 2010]

*Org N was calculated by the difference between the TKN and NH_4^+ concentrations

Chapter Five:

Methods

The project was carried out in four phases. Each of the four phases, including the purpose for each phase, is defined in Table 5.1. This Chapter will discuss each phase in detail, and will define the conceptual model framework for an alternative bioretention system.

Table 5.1. Four phases to develop the alternative bioretention cell model and the purpose for each phase

Phase	Description	Purpose
Phase I	Site-Specific Nutrient Characterization	Nitrogen concentrations needed for SWMM-5 pollutant input parameters
Phase II	Analytical Bioretention System Model	Data from Siegel (2009) were used to estimate first-order rate coefficients for nitrification and denitrification
Phase III	SWMM-5 Hydrologic ABC Model	Site-specific input parameters from the literature were used to develop a ABC model
Phase IV	SWMM-5 Water Quality ABC Model	Treatment expressions were derived in order to estimate nitrogen reductions

Phase I: Site-Specific Nutrient Characterization

In order to define site-specific nitrogen input parameters for the SWMM-5 model designed in this project, it was necessary to characterize the concentrations of nutrients at the proposed bioretention retrofit site. The parameters I analyzed during Phase I were selected because they are typically analyzed in stormwater runoff, as discussed in

Chapter 4. Two separate storm events were analyzed during the dry season, specifically on November 4th and December 11th, 2010. Results of these analyses are provided in Appendix A. The analytes I monitored in this study include the following:

1. Major anions: NO_3^-, NO_2^-,
2. Total N, Total P
3. Organics: BOD, COD
4. Solids: TSS, VSS
5. pH
6. Total coliforms

For both storm events analyzed, the following quality control and assurance steps were followed as closely as possible to ensure accurate results:

1. Analysis of duplicates:

   Duplicate samples were prepared and analyzed the same way as the original sample. Duplicates were used to determine precision.
2. Analysis of reagent blanks:

   Reagent blanks were analyzed whenever a new reagent was used or 5% of the sample load, whichever was greater. The reagent blanks were used to monitor purity. The reagent blanks were run after any sample with a concentration greater than that of the highest standard.
3. Calibration standards:

   At least three dilutions of the standard were measured during an analysis. The reported results were with the range of the dilutions used.

General sample collection and handling followed protocols published in Urban Stormwater BMP Performance Monitoring [USEPA, 2002]. All previously established analytical methods used in the research followed approved methods in the standard compilations [e.g. APHA *et al*., 2005; ASTM, 1994]. Reagent grade chemicals (Fisher Scientific, Pittsburgh PA; Sigma-Aldrich, St. Louis MO) were used for all stock solutions and standards. *Standard Methods* [APHA *et al*. 2005] were used to measure BOD_5 (Method 5210B),, TSS (2540D), VSS (2540E),, total P (4500-PE), and Anions (NO_3^-, NO_2^-). Total N (TN) was measured using persulfate digestion tubes with Hach (Loveland CO) reagents. Organic N concentrations were calculated by difference (TKN - NH_4^+-N). Total coliforms were determined using the membrane filter method [APHA *et al.* 2005; Method 9222A]. pH was measured using an Thermo-Orion (Beverly MA) pH meter. Current method detection limits in our laboratory are (mg L^{-1}): 0.4, 0.3, 0.07, 0.02, 3.0, 20.0, for TN, NO_3^--N, NO_2^--N, TP, BOD and COD, respectively.

A recent study completed by PBS&J [2010] took place in the same year (2010) as the analyses for the present study. PBS&J [2010] found that the analyzed nutrient concentrations and precipitation data were on average the same as the historical data they presented (1915-2009). PBS&J [2010] presented both quantity and quality constituents. Analyses during the PBS&J [2010] study were completed in the same city (Venice, FL), whichshares similar hydrologic characteristics, to the Venice East Blvd. site. Therefore, the analyzed nitrogen concentrations and the PBS&J [2010] concentrations were used in the analyses completed in Phases II, IV and V. These quantity and quality input parameters are discussed in the subsequent sections.

Conceptual Model Development

The alternative bioretention cell (ABC) model presented in this study was adapted from a few similar studies found in the literature [Lucas, 2010; Abi Aad et al. 2010]. The model structure was designed after a recent study by Lucas [2010]. Lucas [2010] thoroughly addresses the conceptual flow of water routing through a layered bioretention cell. However, Lucas [2010] only analyzed the hydrologic components of a bioretention cell and did not analyze nutrient transformations. Therefore, the ABC model structure was adapted for this case study to estimate nitrogen reductions from a system of thirteen alternative bioretention cells, along Venice East Blvd. in Venice, Florida.

Ammonification was assumed to occur rapidly and completely, so NH_4^+-N and Org N are assumed to be a single variable, TKN_i. Conversion of both ammonium to nitrite and nitrite to nitrate was assumed to occur in the aerobic nitrifying (sand) layer. Conversion of nitrate to nitrogen gas was assumed to occur in the submerged anaerobic (mulch) layer. Other mechanisms for nitrogen removal, such as adsorption, plant uptake and volatilization were not considered in this model. However, different nitrogen removal mechanisms, as well as different types of nutrients and contaminants, can be incorporated into future updates of this model. A conceptual diagram of the mechanisms for nitrogen transformation within a bioretention cell is shown in Figure 5.1.

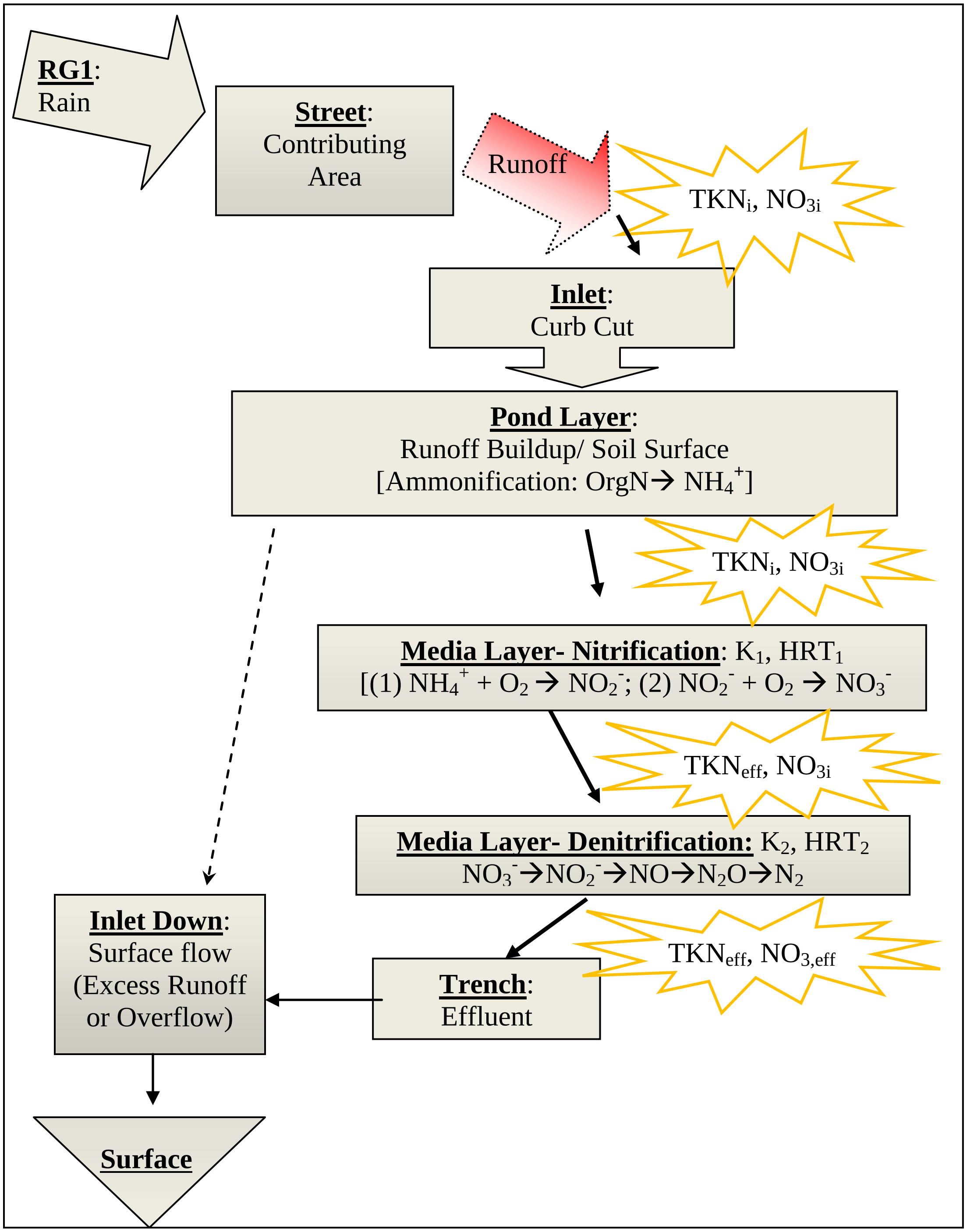

Figure 5.1. Conceptual model framework. Depiction shows the flow of stormwater runoff through a bioretention cell, including the sections where the transformations of each nitrogen constituent (addressed in this study) were assumed to occur. The symbols are defined in the subsequent section.

The model representing the alternative bioretention cells can be conceptually "disaggregated" into various components [Lucas, 2010], in order to more accurately represent the mechanisms for nitrogen removal in each region. SWMM-5 allows for nutrient inputs into one component to be dependent on the output of the previous component [Huber and Dickinson, 1988]. Therefore, the nitrification media layer and the denitrification media layer are linked by nutrient and water flow within the model. This means that the efficiency of total nitrogen removal within the cell will be dependent on the efficiency of nitrification and denitrification in the respective media layers. The mass balances were maintained for both the nitrification and denitrification zone.

Phase II: Analytical Bioretention System Model

First order decay coefficients (k_1 and $k_{2)}$ were needed to develop treatment expressions for the nitrification and denitrification processes occurring in the respective layers of the alternative bioretention cell (ABC) model. The rate coefficients were estimated based on the results from a previous study by Ryan Siegel at the University of Massachusetts, Amherst. Siegel [2009] analyzed a pilot-scale bioretention system (using wood chips in the denitrification layer), run under laboratory conditions. Siegel [2009] analyzed synthetic stormwater using nitrogen feed concentrations based on literature values for urban runoff [Davis *et al*., 2001; Hsieh and Davis, 2005]. The average influent feed composition consisted of 1.5 mg/L of NO_3^--N, 2.1 mg/L of NH_4^+-N and 4 mg/L of Org N. Siegel's [2009] laboratory results showed average effluent concentrations for NO_3^--N, NH_4^+-N and Org N to be < MDL (0.005 mg/L), 0.3 mg/L and 0.6 mg/L, respectively. The flow rate and duration at which the synthetic stormwater was applied to the bioretention unit was 240 ml/min and six hours, respectively. The bioretention area was set at 5% of the drainage area being treated, with a runoff coefficient of 0.15 [Siegel, 2009]. The overall mean HRT was estimated at 4.3 hours [Siegel, 2009].

The HRT_1 and HRT_2 for the nitrification and denitrification layer were estimated using the known volume and flow values presented by Siegel [2009], using the following equation:

$HRT_1 = V1 / Q1 * n$, for the nitrification layer (5.1)

$HRT_2 = V2 / Q2 * n$, for the denitrification layer (5.2)

where, V1 is the volume of nitrification layer, and V2 is the volume of the denitrification layer in the bioreactor (values obtained from Siegel [2009]).), Q1 and Q2 (Q1 = Q2) are the flow rate values (obtained from Siegel [2009]), and *n* is the porosity. Porosity values for the wood chip and sand media were derived from the literature, as discussed in the Chapter 6. These porosity values were used with Siegel's [2009] data to solve for HRT_1 and HRT_2 (where $HRT_1 + HRT_2 = 4.3$ hours, from Siegel [2009]).

An assumption was made that the nitrification and denitrification layers of Siegel's system could both be modeled as plug-flow reactors, and that nitrification and denitrification can both be modeled using first-order reaction kinetics. Therefore, the nitrification and denitrification layers were modeled as ideal plug flow reactors with first order reaction kinetics. Based on these assumptions the following equations were used to solve for k_1 and k_2.

$\mathrm{TKN_{eff}} = \mathrm{TKN_i} e^{-\mathrm{k1*HRT1}}$, for the nitrification layer (5.3)

$\mathrm{NO_{3,eff}} = (\mathrm{NO_{3,i}} + (\mathrm{R\_TKN}_i))\mathrm{e}^{-\mathrm{k2*HRT2}}$, for the denitrification layer (5.4) where, k_1 and k_2 are the rate coefficient values (and are unknown) for nitrification and denitrification, respectively (1/Time).

Phase III: Hydrologic ABC Model

SWMM-5 simulates the hydrologic and water quality simultaneously; however, these two models are discussed separately in this study in order to better clarify the different types of input parameters and their results. In order to develop the ABC model, the hydrologic data needed to be gathered. The data needed for this phase of the project was found in the literature, as discussed. The hydrologic model incorporates site-specific input parameters, as well as hydrologic parameters obtained from the literature. The hydrologic ABC model assumes:

- 100% of the impervious flows will be routed to the system
- Infiltration rate is set at the SWMM-5 default rate
- Fines from the runoff will not clog the system (i.e., adequate maintenance of the system is assumed)
- Hydrologic flows entering the bioretention system will flow through the different layers of media (until the media is saturated)
- The carbon source (wood chips) is assumed to be present in the denitrification layer during each simulation
- Temperature is considered constant at 35° C
- Once the ponding elevation of the system has been exceeded (>30.5 cm), the system will overflow, and excess flows will be sent back into the street, where no further treatment will occur [Lucas, 2010]

The site specific soil infiltration rate parameters were based on soil data found on the Websoil Survey website [USDA, 2010]. The SWMM-5 model representing an alternative bioretention cell system (Figure 5.2) is presented to facilitate the comparison to the conceptual framework (Figure 5.1). Based on the site development plans provided by Sarasota County, the area of each cell will vary only slightly. The provided plans do not define the exact area of each cell, therefore making it impossible to calculate the total area of all the bioretention cells. The plans show each cell individually, and the area of each cell varies only slightly. Therefore, the model was designed based on the approximate area of the thirteen cells; by multiplying the approximate area of one cell by thirteen, to get the total area of the system. Future calibrations could be made to address the exact area of each cell, if the as-built survey data is provided.

The model was designed so that runoff from the street will flow into the cell through a cut in the curb. The curb cut is placed approximately 5 cm (0.16 ft) above the top of the media, to prevent backwash of mulch from the cell [Lucas, 2010]. Runoff that accumulates in the denitrification (mulch) media layer will collect in the underdrain which will then discharge into a 61 cm (24 in.) wide overflow compound v-notch weir 116.8 cm (46 in.) higher. The height of the weir was calculated by adding the depth of the cell (34 in.) to the depth of the ponding layer (12 in.) [Lucas, 2010].

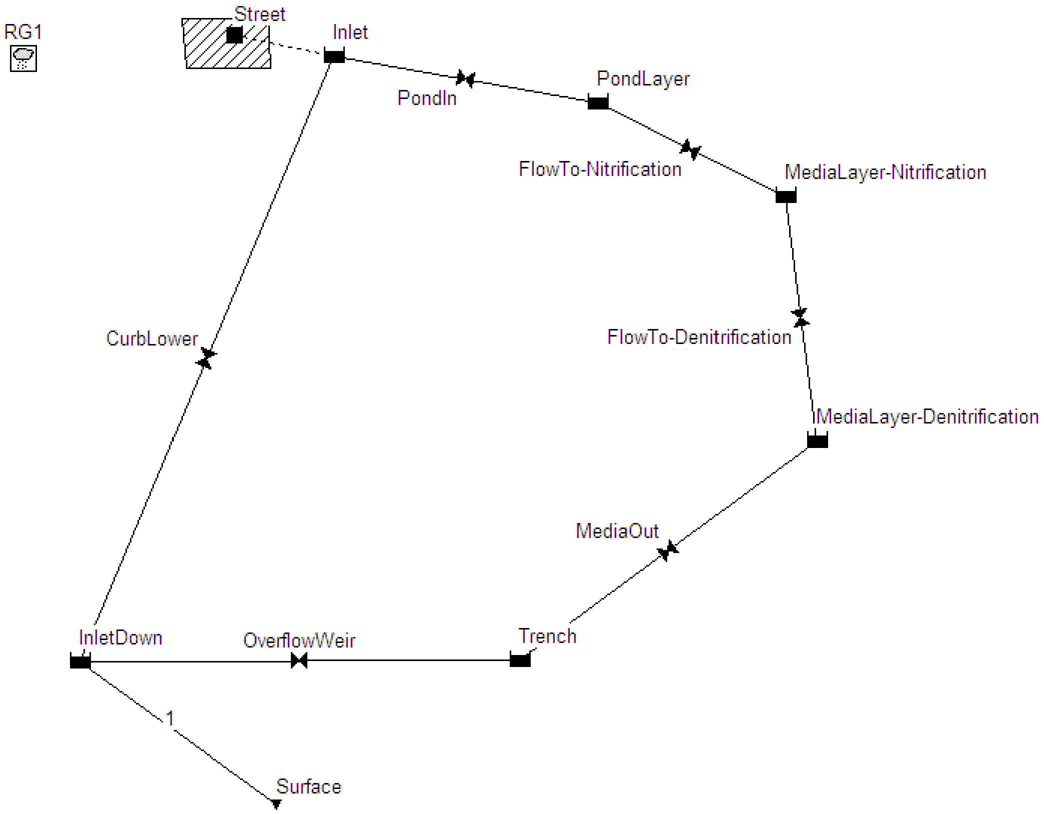

Figure 5.2. SWMM 5.0.22 Model of alternative bioretention cell (ABC)

Site-specific bioretention cell sizing parameters (e.g. height, width, invert elevation, etc.) for the ABC model were derived from Sarasota County's designs. The subcatchment, or contributing area, was quantified by finding the total contributing area, as well as the area of the pervious and impervious potions within the subcatchment. The input parameters for the area of the subcatchment, in this SWMM-5 model, are based on the total area and the percent of the area that is impervious. Table 5.2 shows the physical characteristics for the subcatchment (i.e., the Venice East Blvd. retrofit site).

In the ABC model, each media layer is represented as a storage unit node. Connecting each storage unit node is an orifice object (i.e., the orifice routes flows into and out of each storage unit). The orifice object was used by Lucas [2010] to route flows into the media; this is incorporated in the ABC model to better represent the complexity of unsaturated flow dynamics into and through a layered bioretention system [Lucas, 2010]. By using a quantity of zero for the width of each orifice, the hydrologic flow through the bioretention system is modeled so that the orifice does not increase the time it takes for the runoff to exit the system (the hydraulic residence time, HRT). Table 5.3 defines the storage unit and orifice input parameters needed to calibrate the ABC model.

The outflow (flow leaving the bioretention system) is modeled to exit the system through a weir (titled the Outflow Weir in this model). The height of the weir is set higher than the TrenchLayer storage unit, to prevent flows from the street from reentering the system. According to Lucas [2010], the trench is likely to encounter some infiltration. Lucas [2010] chose a nominal infiltration rate of 2.54 mm/h (0.10 in/hr); however, this model ignores the nominal infiltration rate, and assumes no infiltration will occur in the trench layer. Future calibrations could adjust the infiltration rate in the trench layer.

Table 5.2. Physical characteristics of the subcatchment [calculations are based on Doyle and Miller, 1980; Tsihrintzis and Hamid, 1998].

Characteristic	**Site: Venice East Blvd. Low Density Residential**	**Source for Information**
Site Location	Venice, Sarasota County, FL	Case Study
Total Drainage Area (Subcatchment)	58.39 ac (2,543,289 ft^2)	USGS [2010]
Width (Subcatchment)	163 ft	USGS [2010]
Impervious Area (Street)	24.62 ac (1,063,094 f^2)	USGS [2010]
Pervious Area	33.98 ac (1,477,650 f^2)	Calculated from USGS data
Percent Pervious Area	58.2 %	Calculated from USGS data
Percent Impervious Area	41.8 %	Calculated from USGS data
Overland Flow Slope	2.7 %	Doyle and Miller [1980]; Tsihrintzis and Hamid [1998]
Land Use	Low Density Residential	USGS [2010]
Avg. Lot Size	24 x 30	Doyle and Miller [1980]; Tsihrintzis and Hamid [1998]
Mean Annual Rainfall (1915-2010)	98.12 cm/yr	PBS&J [2010]
Soil Cover	Lawn & Shrubbery	Doyle and Miller [1980]; Tsihrintzis and Hamid [1998]
Soil Description	Myakka Fine Sand	USGS [2010]
Soil Group (SCS)	Fine Sand, poorly drained	USGS [2010]
Soil Capacity	Approximately 18.03 cm (0.59 ft)	USGS [2010]
Vegetation	Lawn sod w/ garden shrubbery and trees	Site Evaluation
Street/ Gutter Description	Curb and gutter	Site Evaluation
Current Pervious Area	Depressed/ grass swale with overflow draining to street	Site Evaluation
Proposed Pervious Area	Depressed area- drainage into bioretention cell, and overflow draining to street	Site Evaluation

Table 5.3. Storage unit and orifice input parameters (based on system designs presented in Chapter 3).

Depth of the Bioretention System	86.26 cm (2.83 ft)
Inlet Storage Unit (the subcatchment drains into here)	Height= 91.14 cm (2.99 ft) (set 5cm above the top of pond layer to prevent backwash)
	Depth= 304.8 cm (10ft)
	Width= 914.10 cm (29.99 ft)
PondIn Orifice (drains from Inlet to Ponding layer)	Height= 86.26 cm (2.83 ft)
	Width= 0 cm
PondLayer Storage Unit	Invert Elevation= 86.26 cm (2.83 ft)
	Max Depth= 15.24 cm (1 ft)
	Initial Depth= 0 cm (initial ponded depth)
	Ponded Area= 914.10 cm^2 (1 ft x 29.99ft)
FlowTo-Nitrification Orifice	Height= 55.78 cm (1.83 ft)
	Width= 0 cm
MediaLayer-Nitrification Storage Unit	Invert Elevation= 55.78 cm
	Max Depth= 48.16 cm (soil + mulch layers)
	Ponded Area= 1444.14 cm^2 (47.38 ft^2)
FlowTo-Denitrification Orifice	Height= 7.62 cm (0.25 ft)
	Width= 0 cm
MediaLayer-Denitrification Storage Unit	Invert Elevation= 7.62 cm (0.25 ft)
	Max Depth= 15.24 cm (0.5 ft)
	Ponded Area= 15 ft^2
MediaOut Orifice	Height= 0.01 ft
	Depth= 0 cm
Trench Storage Unit	Height= 0.01 ft
	Invert Elevation= 0 ft
	Depth= 0 ft

Specific input parameters used to develop the ABC model are based on studies by Doyle and Miller [1980] and summarized by Tsihrintzis and Hamid [1998]. These input parameters include: overland flow slopes, Manning's roughness value (Manning's *n*), pipe flow roughness, saturated hydraulic conductivity (K_s) and the impervious and pervious depression storage of the subcatchment. These parameters are based on data acquired by Doyle and Miller [1980], in a report issued by the United States Geological

Survey (USGS), for an evaluation of 231 storm events in Southwest Florida. Tsihrintzis and Hamid [1998] used the data from the USGS report to calibrate a SWMM model for small urban catchments in Southwest Florida. Doyle and Miller [1980] present all information relevant to the calibration of the model developed by Tsihrintzis and Hamid [1998]. These input parameters are shown in Table 5.4. Specific calibration and verification details are reported in the previous studies by Doyle and Miller [1980] and Tsihrintzis and Hamid [1998]. The average capillary suction head, initial moisture deficit and saturated hydraulic conductivity are not applicable at the wetting front in the ABC model, as flows route to the subsequent storage unit (i.e., flow does not infiltrate into the underlying soil).

The ABC model presented in this study, to predict post-development nitrogen concentrations for the Venice East Blvd. bioretention cell retrofit site, is based in part on the SWMM calibration data presented by Tsihrintzis and Hamid [1998]. This is because the SWMM model presented by Tsihrintzis and Hamid [1998] was designed after a site in SW Florida, only a few hours away from the Venice, FL study site. Therefore, it is assumed that these sites will share identical hydrological and physical characteristics. Detailed descriptions of the SWMM calibration process and precipitation data (including single-event rainfall data) are discussed in detail by Tsihrintzis and Hamid [1998].

Table 5.4. Quantity input parameters [presented and verified by Tsihrintzis and Hamid, 1998].

Land Use		Manning's *n*			Dstore-Imperv Impervious Depression Storage (mm)	Dstore-perv Pervious Depression Storage (mm)	Average Capillary Suction Head at wetting front [S_u (mm)]	Initial Moisture Deficit (mm/mm)	Saturated Hydraulic Conductivity [K_s (mm/h)]
		Pipe	Pervious Surface	Impervious Surface					
Low Density Residential	Literature	0.011- 0.013 *	0.10-0.20 ¥	0.010-0.015 ¥	0.3-2.3 ¥	2.5-5.1 ¥	9.7- 253 Ψ	0.37-0.50 Ψ	8.6-119 Ψ
	Used for Calibration	0.013	0.106	0.013	1.0 (.04 in)	5.1 (0.2 in)	N/A	N/A	N/A

* Wanielista and Yousef [1993]
¥ Huber and Dickinson [1988]
Ψ Chow et al., [1988]

Tsihrintzis and Hamid [1998] calibrated their SWMM model based on sixteen independent storm events presented by Doyle and Miller [1980]; which included three storm events for low-density, single-family residential land use from the. The location of the study site presented in this paper is considered high-density, single-family residential land use [USGS, 2010; USEPA, 2010]. The low-density, single-family residential site is the largest of the sites studied, with a mean annual rainfall of 63 inches (1575 mm) [Tsihrintzis and Hamid, 1998]. This data is comparable to the historical rainfall data presented by PBS&J [2010].

Six independent storm events were selected from the Doyle and Miller [1980] study (Table 5.5). These events were randomly selected, based on seasonal precipitation variability. Three events were randomly selected from the rainy season and three from the dry season, because the dry weather conditions will typically see greater fluxes of nitrogen (i.e., the first flush), due to the build-up of Org N and NO_3^- on the soil surface after a prolonged period of drought [USEPA, 2010]. In addition to the seasonal constraints, the rainfall events could not exceed the monthly precipitation totals found in the same months in the historical rainfall data; which was presented by PBS&J [2010] (shown in Table D.1 in Appendix D). More details about the concentrations of the nitrogen species analyzed in this study are provided in the subsequent section. After running these six, single-event precipitation simulations, the observed data were compared to the simulated runoff (Table 5.6).

Table 5.5. Model quantity calibration data: single-family residential site [based on findings presented by Doyle and Miller, 1980].

Storm #	Storm Date	Time Interval	Rainfall (in)	Observed Runoff (in.)	Observed Peak Q (ft^3/sec)
1	01-13-74	0720-0990	0.810	0.0980	2.82
3	04-15-74	0364-0480	0.600	0.0590	3.79
45	12-26-74	1271-1380	0.140	0.0100	0.570
57	06-17-74	0667-0840	1.25	0.0840	32.8
73	07-19-74	0305-0630	1.92	0.400	22.1
84	09-18-74	0860-1440	4.37	0.800	27.1

Phase IV: Water Quality ABC Model

The design of the water quality ABC model was developed using the following assumptions:

- 100% Conversion of OrgN → NH_4^+ occurs in the Ponding Layer
- All nitrification occurs in the nitrification layer, all denitrification in the denitrification layer.
- Nitrite was considered an intermediary species; therefore, all nitrite/nitrate in the system was available for decomposition.
- Denitrification will occur at micro-sites within the anoxic bioflim layer associated with the denitrification media; therefore, the dissolved oxygen concentration in the bulk liquid is ignored (i.e., denitrification will occur)
- Plant uptake, volatilization and adsorption are not considered in this model (i.e., only nitrification and denitrification are considered)

In N removing bioretention cells, total N removal can occur in the following steps: adsorption and filtration of Org N and adsorption of NH_4^+ during the wetting period, ammonification of retained Org N and nitrification of NH_4^+ as oxygen reenters the pores during the drying period, and denitrification in the submerged zone during subsequent wetting periods utilizing the solid substrate wood (e.g. mulch) as the electron donor [Ergas et al., 2010]. In the ABC model, only nitrification and denitrification are considered. Based on the literature, for low-density residential neighborhoods, the most relevant sources of nitrogen for this project will be Org N, NH_4^+-N, and NO_3^--N [USEPA, 2010], NO_2^- concentrations were assumed negligible. Considering TKN is the sum of Org N and NH_4^+-N, TKN was tracked in SWMM-5 as well as NO_3^--N.

The following treatment expressions were used to evaluate the mass (lbs/event) of TKN and NO_3^--N in the effluent.

$$\mathrm{TKN_{eff}} = \mathrm{TKN_i} e^{(-\mathrm{k1*HRT1})}, \text{ for the nitrification layer} \tag{5.5}$$

$$\mathrm{NO_{3,eff}} = (\mathrm{NO_{3,i}} + (\mathrm{R\_TKN_i}))\mathrm{e}^{(-\mathrm{k2*HRT2})}, \text{ for the denitrification layer} \tag{5.6}$$

where, $\mathrm{R\_TKN_i}$. is the mass of the $\mathrm{TKN_i}$ reacted, found in equation 5.5 (i.e., the $\mathrm{R\_TKN_i} = \mathrm{TKN_i} - \mathrm{TKN_{eff}}$), k_1 and k_2 are the rate loss coefficient values estimated in Phase II. Equation 5.5 was used in the treatment expression dialog box in SWMM-5, in the nitrification layer of the ABC model. Using a defined $\mathrm{TKN_i}$ concentration (mg/L), with the treatment expression (equation 5.5) input into the nitrification layer, SWMM-5 quantified the reacted TKN (lbs/event). The method for estimating NO_3^- removal using the ABC model is described below.

SWMM-5 was able to solve for the removal of TKN_i (R_TKN_i) during simulation runs. However, it could not directly solve for the removal of NO_3^-. In order to solve equation 5.6, the volume and flow were divided at each time step (30 minute interval) to find the HRT in the denitrification layer at each time step. The HRT at each time step was then used to solve equation 5.6 (at each time step). SWMM-5 gives TKNi, R_TKNi, and NO_3^- in lbs/event. This number represents flow multiplied by the concentration. The TKNi and NO_3^- loads (lbs/event) were then found for each concentration shown in Table 5.6. Solving equation 5.6, the results were used to find the average pollutant removal efficiency for the EPA Sarasota sized ABC systems for each event, for the four concentrations shown in Table 5.6. Once the average pollutant removal efficiencies were found, the TN load reduction was derived, including the TN removal rates for both the EPA and Sarasota sized ABC systems.

The precipitation data presented in the previous section were analyzed at a different site (in SWFL) from where the site-specific nitrogen concentrations were analyzed in Phase I; therefore, it was necessary to simulate each nitrogen concentration as a sampling distribution. The uncertainty for each parameter is specified by using a minimum, median, maximum and observed value. The benefit of using a range of nitrogen concentrations is that, it allows for a less site-specific model (i.e., the results can be used to estimate loading rates at various sites across SWFL, assuming the sites share similar physical characteristics). The range of nitrogen concentrations used for simulating loading from the stormwater runoff are presented in Table 5.6. The concentrations used are based on the concentrations seen in both the PBS&J [2010] study and the field sampling done during this study.

Table 5.6. Nitrogen species in runoff; used to calibrate the SWMM-5 model [adapted from PBS&J, 2010 and field sampling data].

Constituent	**Minimum Concentration (mg/L)**	**Median Concentration (mg/L)**	**Maximum Concentration (mg/L)**	**Analyzed Concentration (mg/L)**
$NO_2^-/NO3^-$	0.000	0.420	1.80	1.48
NH_4^+-N	0.010	0.310	1.22	1.55
Org N	0.350	5.28	15.9	1.38

Chapter Six:

Results and Discussion

Phase I: Site-Specific Nutrient Characterization Results

For two separate storm events I analyzed the analytes shown in Table 6.1 at the Venice East Blvd. bioretention retrofit site, in order to quantify the pre-developed nutrient characteristics. Both storm events occur in the dry season; November 14th and December 11th. The average concentrations for the various parameters measured are shown in Table 6.1. The standard deviations from the average values are shown in parentheses.

Table 6.1 Results of November 4th and December 11th, 2010 stormwater runoff samples.

Analyte	November 4th Concentration	December 11th Concentration	Units
TN	1.70 (0.170)	1.30 (0.660)	mg/L
TP	0.11 (0.020)	0.170 (0.010)	mg/L
NO_2^-/NO_3^-	0.570 (0.450)	0.430 (0.190)	mg/L
Total Coliforms	27.0 (4.71)	24.0 (3.17)	CFU/100 mL
pH	7.89 (0.190)	7.53 (0.510)	0-14 pH units
DO	6.55 (0.290)	7.21 (4.42)	mg/L
BOD_5	4.70 (1.29)	3.87 (0.340)	mg/L
TSS	22.2 (3.15)	28.7 (0.490)	mg/L
VSS	11.2 (2.41)	16.3 (0.140)	mg/L

*Standard deviations given in (). Triplicates samples were used during analyses to determine the standard deviations.

The results from the laboratory analyses indicate that there was a greater concentration of TN seen in the November 4th analysis, compared to the December 11th analysis. Although hydrologic data were not quantified during these two events, it was noted that the November 4th event was much more intense and last approximately 6 hours. In comparison, the December 11th event was a very mild storm event, with rainfall only lasting approximately 2 hours. The results from this Phase compared well with the typical concentrations found in the literature (Table 4.1).

Phase II: Analytical Bioretention System Model Results

Results from a pilot-scale bioretention system, run under laboratory controlled conditions, were used to estimate the mean HRT_1 (for nitrification) and the mean HRT_2 (for denitrification), as discussed in Chapter 5. The porosity of sand and wood chip was assumed to be 0.25 and 0.25, respectively [Robertson, 2010; Ima and Mann, 2007]. Although the literature defined the porosity of wood chips to be between 0.45 and 0.63 [Ima and Mann, 2007], the 0.25 porosity value was chosen so that the HRT of the system would be equal to the 4.3 hours found by Siegel [2009]. The literature notes that wood chip porosity varies greatly depending on the type of wood, the size of the chips and whether the wood was moist prior to the pulse tracer study [Ima and Mann, 2007]. Using these porosity values and the volume and flow presented by Siegel [2009], the estimated mean HRT_1 value for the nitrification layer was 2.87 hours, and the estimated mean HRT_2 value for the denitrification layer was 1.43 hours.

Using these HRT values to solve equations 5.3 and 5.4, the reaction rate coefficients for nitrification and denitrification were found to be 0.70/hour and 5.2/hour, respectively. A recent study found similar k-values for the rate of denitrification, 0.19/min [Warneke et al., 2011]. As the reaction rate of denitrification is dependent on other variables besides the HRT (e.g. temperature, dissolved oxygen concentration, surface areas, moisture content, electron donor availability, etc.), the k-values estimated during Phase II of this study seem to compare well to the literature [Warneke et al., 2011; Greenan et al., 2006, 2009; Groffman et al., 2006].

Phase III: Hydrologic ABC Model Results

Lucas [2010] discusses that designing the model with this disaggregated routing leads to “unexpected behavior” during simulation events, as the “various compartments fill and empty at different rates”. Results from the simulations for the six separate storm events modeled for this study also showed this same unexpected behavior; however, the hydrologic behavior seemed a bit extreme when comparing results with Lucas [2010], due to the sharp flow peaks seen in the various compartments of the system (Figure 6.1). These peaks result from the continuous filling and draining of the inadequately sized pond layer. The September 18th, storm event was 4.37 inches (the largest storm event simulated) over nine and a half hours. Most of the flow during this event was routed to the curb lower orifice, and did not enter the system. After careful deliberation, it was discovered that the Sarasota bioretention system design area was sized at only 1% of the total drainage area. The system being sized this small was affecting the hydrologic performance of the model.

To confirm the validity of these results, a new ABC model was designed based on the bioretention cell sizing specifications defined by the EPA (bioretention system area should be approximately 5-7% of the drainage basin area) [USEPA, 2000]. The resized ABC model was designed with a larger area, which was designed at approximately 6% of the subcatchment area. The hydrologic results and nutrient transformations in the ABC model based on EPA sizing guidelines showed much better results for storm events exceeding 1 inch. Hydrologic performance of the ABC model designed based on the sizing specifications defined by the USEPA are presented in Figure 6.2 to facilitate comparison to the ABC model design based on Sarasota County's plans; the results in Figure 6.2 also compare nicely with the results presented by Lucas [2010].

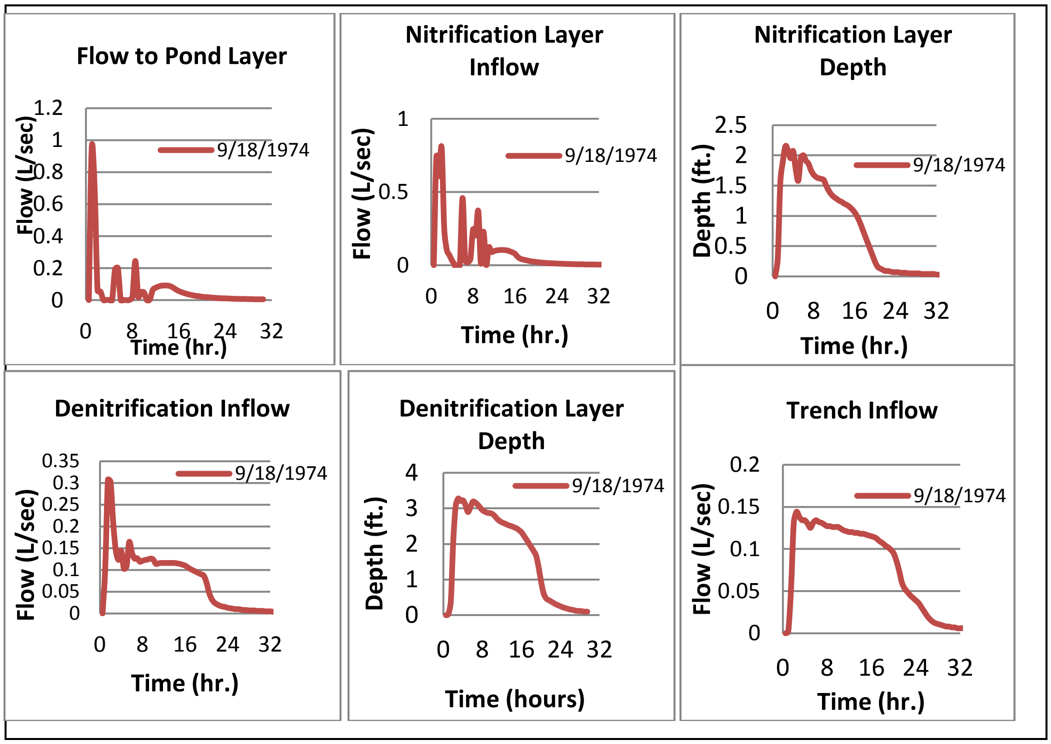

Figure 6.1. Flow through the orifice controlled system for a 4.37-in. simulated storm event for system sized according to Sarasota's plans.

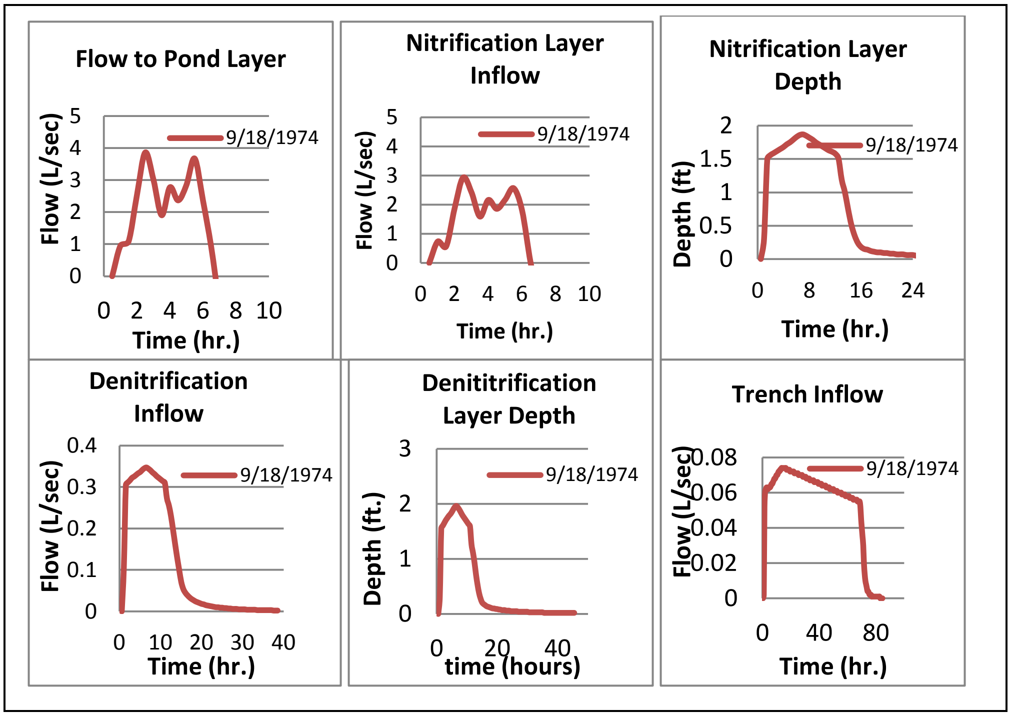

Figure 6.2. Flow through the orifice controlled system for a 4.37-inch simulated storm event in system sized according to USEPA guidelines.

Simulations were run to compare effluent quantity using infiltration rates defined by Lucas [2010] in each of the storage unit/layers. Results from these simulations showed that no substantial difference in hydraulic performance. Site-specific infiltration rates were not defined in this study. Considering results were relatively identical with or without infiltration rates being defined in the storage units, infiltration rates into the surrounding soils of each storage unit layer were ignored in both of the final ABC models (the Sarasota sized system and the redesigned, larger system). In the future, assuming infiltration rates are available, it may be useful to define infiltration rates for each storage unit/layer.

The results show that more runoff routed through the larger system than the smaller system, and the overall maximum HRT of the larger system was substantially greater (by almost 2 days), then the overall maximum HRT in the smaller system. Based on these simulated HRT values, it was no surprise that the efficiency to achieve nitrification and denitrification was much better in the larger system, than in the smaller.

Phase IV: Water Quality ABC Model Results

Six simulations were run in SWMM-5 for the six separate storm events using a range of concentrations (Table 5.6). The minimum TKN_{eff} and $NO_3^-{}_{eff}$ concentrations (mg/L) vs. time (hours) from the nitrification layer are shown in the Figures below for the Sarasota sized ABC model (Figure 6.3) and the EPA sized ABC model (Figure 6.4), for the 4.37-inch simulated storm event. These graphs show a peak of TKN_{eff} (less than 0.36 mg/L) as the flow enters the denitrification layer (when the HRT is too short and does not allow for efficient nitrification transformations). Due to the smaller size of the ponding layer in the Sarasota sized ABC model, the TKN_{eff} has completely passed through the denitrification layer much more rapidly than it has in the EPA sized ABC model. In addition, the increased time interval in the EPA sized ABC model is due to the fact that more stormwater runoff has infiltrated into the EPA sized ABC model, because of its larger size. Therefore, these flows take longer to drain out of the system completely.

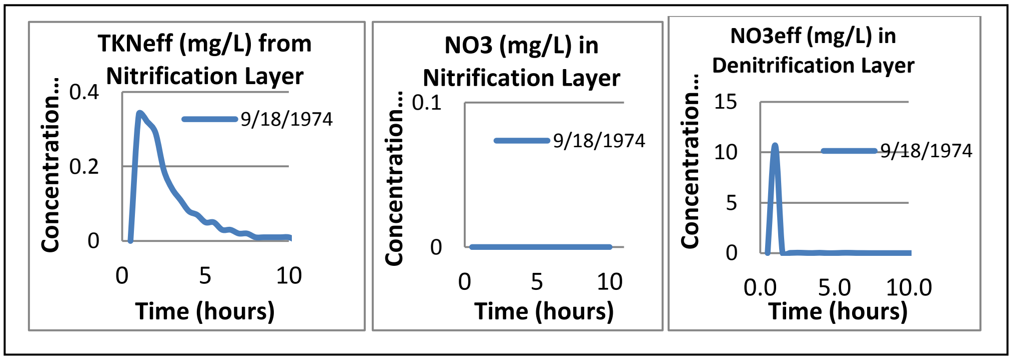

Figure 6.3. TKN_{eff} and $NO_3^-{}_{eff}$ concentrations vs. time in Sarasota sized model.

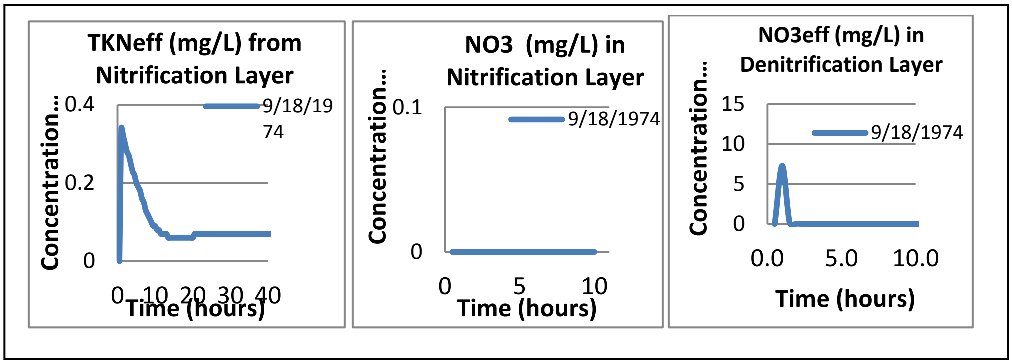

Figure 6.4. TKN_{eff} and $NO_3^-{}_{eff}$ concentrations vs. time in EPA sized model.

The pre-development event loading rates for the six separate storm events were simulated in SWMM-5. The results from these six separate event simulations are shown for the TKN loading rates (Table 6.2), and for the event NO_3^- loading rates (Table 6.3). During the dry season, it is probably unrealistic to assume that you would see minimum concentrations of nitrogen in stormwater runoff. Generally, after long dry periods, nutrients build up on the ground surface; therefore, it is likely that nitrogen loading rates would be closer to the median event loading rate. In comparison, it is probably unrealistic to assume that during the rainy season you would see the maximum nitrogen loading rates. Typically, wet weather flushes the nutrients off the soil surface; therefore, during wet years, you would likely see concentrations closer to the minimum event loading rates. If the results were shown as annual N loading rates, using a range of concentrations would result in unrealistic outcomes. Therefore, the annual N loads were not calculated in this study.

Table 6.2. SWMM-5 simulated pre-development TKN loading rates for six separate storm events.

Event	Rainfall (in)	Event loading rate (lbs) assuming minimum TKN conc.	Event loading rate (lbs) assuming median TKN conc.	Event loading rate (lbs) assuming maximum TKN conc.	Event loading rate (lbs) assuming analyzed TKN conc.
1/13/1974	0.810	1.93	29.3	91.8	15.7
4/15/1974	0.600	1.43	22.2	68.0	11.6
6/17/1974	0.140	0.330	5.17	15.9	2.71
7/19/1974	1.25	2.98	46.2	132	24.2
79/18/1974	1.92	4.95	71.0	218	37.2
12/26/1974	4.37	10.4	161	495	84.6

Table 6.3. SWMM-5 simulated pre-development NO_3^- loading rates for six separate storm events

Event	Rainfall (in)	Event loading rate (lbs) assuming minimum NO_3^- conc.	Event loading rate (lbs) assuming median NO_3^- conc.	Event loading rate (lbs) assuming maximum NO_3^- conc,	Event loading rate (lbs) assuming analyzed NO_3^- conc.
1/13/1974	0.810	0.000	2.25	9.64	7.93
4/15/1974	0.600	0.000	1.67	7.14	5.87
6/17/1974	0.140	0.000	0.39	1.67	1.37
7/19/1974	1.25	0.000	3.47	14.9	12.2
79/18/1974	1.92	0.000	5.33	22.9	18.8
12/26/1974	4.37	0.000	12.12	52.0	47.7

By inputting equation (5.5) into the nitrification layer, SWMM-5 estimated the efficiency of the system to achieve nitrification (Tables 6.4 through 6.7). SWMM-5 output data from these simulations can be found in Appendix D. The mass TKNi that reacted is about the same for each simulation. Therefore showing results are consistent for each simulation. The denitrification results are discussed in detail in the following paragraphs.

Table 6.4. Simulated efficiency of nitrification in ABC models, for the six storm events analyzed at the minimum nitrogen concentration.

Event	System	TKNi (lbs)	Average Mass Reacted (%)	Average TKN, effluent (lbs)	Average TKN load reduction (lbs/event)
1/13/1974	Sarasota Sized	0.76	0.34	0.50	0.26
	EPA Sized	0.76	1.0	0.00	0.76
4/15/1974	Sarasota Sized	0.55	0.44	0.31	0.24
	EPA Sized	0.55	1.0	0.00	0.55
6/17/1974	Sarasota Sized	1.2	0.23	0.93	0.27
	EPA Sized	1.2	0.81	0.23	0.97
7/19/1974	Sarasota Sized	1.9	0.17	1.6	0.31
	EPA Sized	1.9	0.66	0.63	1.2
9/18/1974	Sarasota Sized	4.3	0.12	3.8	0.50
	EPA Sized	4.3	0.54	2.0	2.3
12/26/1974	Sarasota Sized	0.09	1.0	0.00	0.09
	EPA Sized	0.09	1.0	0.00	0.09

*Minimum nitrogen concentration: TKN_i= 0.36 mg/L, NO_3^--N= 0 mg/L

Table 6.5. Simulated efficiency of nitrification in ABC models, for the six storm events analyzed at the median nitrogen concentration.

Event	System	TKNi (lbs)	Average Mass Reacted (%)	Average TKN, effluent (lbs)	Average TKN load reduction (lbs/event)
1/13/1974	Sarasota Sized	12	0.34	7.7	4.3
	EPA Sized	12	1.0	0.00	12
4/15/1974	Sarasota Sized	9.0	0.45	4.8	4.2
	EPA Sized	9.0	1.0	0.00	9.0
6/17/1974	Sarasota Sized	19	0.14	14	5.0
	EPA Sized	19	0.81	3.6	15
7/19/1974	Sarasota Sized	30	0.17	24	6.0
	EPA Sized	30	0.66	9.8	20
9/18/1974	Sarasota Sized	67	0.12	59	8.0
	EPA Sized	67	0.54	31	36
12/26/1974	Sarasota Sized	1.4	1.0	0.00	1.4
	EPA Sized	1.4	1.0	0.00	1.4

*Median nitrogen concentration: TKN_i= 5.39 mg/L, NO_3^--N= 0.42 mg/L

Table 6.6. Simulated efficiency of nitrification in ABC models, for the six storm events analyzed at the maximum nitrogen concentration.

Event	System	TKNi (lbs)	Average Mass Reacted (%)	TKN, effluent (lbs)	Average TKN load reduction (lbs/event)
1/13/1974	Sarasota Sized	36	0.34	24	12
	EPA Sized	36	1.0	0.00	36
4/15/1974	Sarasota Sized	26	0.43	15	11
	EPA Sized	26	1.0	0.00	26
6/17/1974	Sarasota Sized	57	0.23	44	13
	EPA Sized	57	0.81	11	46
7/19/1974	Sarasota Sized	89	0.17	74	15
	EPA Sized	89	0.66	30	59
9/18/1974	Sarasota Sized	204	0.12	180	24
	EPA Sized	205	0.54	95	110
12/26/1974	Sarasota Sized	4.3	1.0	0.00	4.3
	EPA Sized	4.3	1.0	0.00	4.3

*Maximum nitrogen concentration: TKN_i= 17.14 mg/L, NO_3^--N= 1.8 mg/L

Table 6.7. Simulated efficiency of nitrification in ABC models, for the six storm events analyzed at the analyzed nitrogen concentration.

Event	System	TKNi (lbs)	Average Mass Reacted (%)	TKN, effluent (lbs)	Average TKN load reduction (lbs/event)
1/13/1974	Sarasota Sized	6.2	0.34	4.1	2.1
	EPA Sized	6.2	1.0	0.00	6.2
4/15/1974	Sarasota Sized	4.5	0.44	2.5	2.0
	EPA Sized	4.5	1.0	0.00	4.5
6/17/1974	Sarasota Sized	9.7	0.23	7.5	2.2
	EPA Sized	9.7	0.81	1.9	7.8
7/19/1974	Sarasota Sized	15	0.17	13	2.0
	EPA Sized	15	0.66	5.1	9.9
9/18/1974	Sarasota Sized	35	0.12	31	4.0
	EPA Sized	35	0.54	16	19
12/26/1974	Sarasota Sized	0.73	1.0	0.00	0.73
	EPA Sized	0.73	1.0	0.00	0.73

*Analyzed nitrogen concentration: TKN_i= 2.93 mg/L, NO_3^--N= 1.48 mg/L

The results presented in Table 6.4-6.7 show that the mean percent of TKN reacted in the Sarasota sized ABC model was 38%, compared to a mean of 84% in the EPA sized system. The December 26th storm event was the lightest rain event of all six storm events; only 0.14 inches of rain. When comparing the results of the December 26th simulation, the output data shows that both the Sarasota and EPA sized ABC models were capable of achieving 100% conversion of the TKN. However, the results shown that for the other five rain events the EPA sized ABC model was much more efficient at achieving nitrification.

The rate of denitrification was not directly solved by the ABC model. The HRT was estimated based on the SWMM-5 output data, for each storm event (discussed in Chapter 5). The reacted TKN concentration (R_TKN$_i$) was combined with the NO_{3i}^--N concentration, in order to estimate the concentration of NO_3^--N coming into the denitrification layer. Appendix D shows detailed SWMM-5 output data used to solve equation 5.6. The estimated HRT values for each time step were then used to solve the first-order denitrification reaction (equation 5.6) and the percent mass that reacted for each time step. The average percent mass reacted was then used to estimate the average event load reduction (lbs/event). The results from these calculations are presented in Tables 6.8-6.11. The results from this Phase of the study indicate that the EPA sized ABC system would achieve on average the highest rates of nitrification (84%), and saw overall nitrogen removal rates (lbs/event) by as much as 87% (Tables 6.8-6.11). Although both systems were capable of achieving the same (on average) denitrification rates (96%), the EPA sized system reduced a much larger overall mass of total nitrogen (lbs/event) than the Sarasota sized system.

Table 6.8. Simulated efficiency of denitrification in ABC models, for the six storm events analyzed at the minimum nitrogen concentration.

Event	System	NO_{3i} (lbs)	Average Mass Reacted (%)	Average NO_3, effluent (lbs)	Average NO_3^- load reduction (lbs/event)	Average TN load remaining (lbs/event)
1/13/1974	Sarasota Sized	0.26	0.96	0.01	0.25	0.51
	EPA Sized	0.76	0.96	0.03	0.73	0.73
4/15/1974	Sarasota Sized	0.24	0.96	0.01	0.23	0.47
	EPA Sized	0.55	0.96	0.02	0.53	0.53
6/17/1974	Sarasota Sized	0.27	0.97	0.01	0.26	0.53
	EPA Sized	0.97	0.97	0.03	0.94	0.94
7/19/1974	Sarasota Sized	0.31	0.96	0.01	0.30	0.61
	EPA Sized	1.2	0.96	0.04	1.2	1.2
9/18/1974	Sarasota Sized	0.50	0.96	0.01	0.48	0.48
	EPA Sized	2.3	0.96	0.09	2.2	2.2
12/26/1974	Sarasota Sized	0.09	0.96	0.00	0.09	0.09
	EPA Sized	0.09	0.96	0.00	0.09	0.09

*Minimum nitrogen concentration: TKN_i= 0.36 mg/L, NO_3^--N= 0 mg/L

Table 6.9. Simulated efficiency of denitrification in ABC models, for the six storm events analyzed at the median nitrogen concentration.

Event	System	NO_{3i} (lbs)	Average Mass Reacted (%t)	Average NO_3, effluent (lbs)	Average NO_3^- load reduction (lbs/event)	Average TN load remaining (lbs/event)
1/13/1974	Sarasota Sized	4.9	0.96	0.12	4.7	5.1
	EPA Sized	13	0.96	0.50	12	12
4/15/1974	Sarasota Sized	4.4	0.96	0.18	4.2	4.7
	EPA Sized	9.2	0.96	0.37	8.8	9.3
6/17/1974	Sarasota Sized	5.6	0.97	0.17	5.4	6.2
	EPA Sized	16	0.97	0.48	16	16
7/19/1974	Sarasota Sized	7.0	0.96	0.28	6.7	7.9
	EPA Sized	21	0.96	0.84	20	22
9/18/1974	Sarasota Sized	13	0.96	0.53	12	12
	EPA Sized	41	0.96	1.64	39	39
12/26/1974	Sarasota Sized	1.5	1.0	0.00	1.5	1.5
	EPA Sized	1.5	1.0	0.00	1.5	1.5

*Median nitrogen concentration: TKN_i= 5.39 mg/L, NO_3^--N= 0.42 mg/L

Table 6.10. Simulated efficiency of denitrification in ABC models, for the six storm events analyzed at the maximum nitrogen concentration.

Event	System	NO_{3i} (lbs)	Average Mass Reacted (%)	Average NO_3, effluent (lbs)	Average NO_3^- load reduction (lbs/event)	Average TN load remaining (lbs/event)
1/13/1974	Sarasota Sized	16	0.96	0.64	15	15
	EPA Sized	40	0.96	1.6	38	38
4/15/1974	Sarasota Sized	14	0.96	0.56	13	13
	EPA Sized	30	0.96	1.2	29	38
6/17/1974	Sarasota Sized	19	0.95	0.95	18	18
	EPA Sized	52	0.97	1.6	50	50
7/19/1974	Sarasota Sized	24	0.96	0.96	23	23
	EPA Sized	68	0.96	2.7	65	66
9/18/1974	Sarasota Sized	40	0.96	1.6	38	44
	EPA Sized	131	0.96	5.2	126	130
12/26/1974	Sarasota Sized	4.7	0.96	0.19	4.5	4.6
	EPA Sized	4.7	0.96	0.19	4.5	4.6

*Maximum nitrogen concentration: TKN_i= 17.14 mg/L, NO_3^--N= 1.8 mg/L

Table 6.11. Simulated efficiency of denitrification in ABC models, for the six storm events analyzed at the analyzed nitrogen concentration.

Event	System	NO_{3i} (lbs)	Average Mass Reacted (%)	Average NO_3, effluent (lbs)	Average NO_3^- load reduction (lbs/event)	Average TN load remaining (lbs/event)
1/13/1974	Sarasota Sized	5.3	0.96	0.21	5.0	5.6
	EPA Sized	11	0.96	0. 44	11	11
4/15/1974	Sarasota Sized	4.3	0.96	0.17	4.2	4.4
	EPA Sized	9.5	0.96	0.38	9.1	9.7
6/17/1974	Sarasota Sized	7.3	0.97	0.22	7.1	7.4
	EPA Sized	13	0.97	0.39	13	14
7/19/1974	Sarasota Sized	10	0.96	0.40	9.6	9.9
	EPA Sized	18	0.96	0.72	17	19
9/18/1974	Sarasota Sized	22	0.96	0.88	21	22
	EPA Sized	37	0.96	1.5	36	38
12/26/1974	Sarasota Sized	1.1	0.96	0.04	1.1	1.2
	EPA Sized	1.1	0.96	0.04	1.1	1.2

*Analyzed nitrogen concentration: TKN_i= 2.93 mg/L, NO_3^--N= 1.48 mg/L

Chapter Seven:

Conclusions

The overall goal of this research project was to estimate nitrogen removal from stormwater runoff for a proposed alternative bioretention system in Venice, FL. The development and calibration of the ABC model took place in four separate phases. Phase I was the quantification of quantity and quality input parameters, which were based on site-specific analyses and the literature. Phase II used analytical methods to derive the rate coefficients for nitrification and denitrification. Phase III and IV was running simulations in SWMM-5 to estimate the quantity and quality of the effluent from the proposed bioretention system.

Phase II of ABC model development was based on previous research conducted by Ryan Siegel, at the University of Massachusetts, Amherst in June 2008. The results of this research were used to determine first order rate coefficients for nitrification and denitrification. These values were then used in the treatment expressions needed to calibrate the SWMM-5 model. Based on the hydraulic residence time determined by Siegel, the nitrification and denitrification first order rate coefficients were determined to be 0.70/hour and 5.2/hour, respectively.

Upon completion of Phase I and II, the ABC model was developed in SWMM-5, and used to run quantity and quality simulations for Phases III and IV. The results of these simulations were used to compare the annual nitrogen loading rates of the post-developed bioretention system site to the pre-developed site. The results from these simulations showed that the system was experiencing flooding in the various compartments of the system for simulated rain events that exceeded 1-inch. These results led to the evaluation of the hydrologic performance of the ABC model (designed after plans provided by Sarasota County).

A new model was developed to compare the performance with the model designed after Sarasota County's specifications. The new model was designed with a total area equal to 6% of the subcatchment area. The larger sized (6%) ABC model and smaller sized (1%) ABC model were then used to simulate the same quantity and quality results. The results from both the Sarasota sized system and the redesigned system (based on EPA's bioretention sizing guidelines; 5% of the impervious portion of the subcatchment) were then used to compare to annual loading rates of the post-developed bioretention site to the pre-developed site. Comparing the simulation results from both models showed that the larger bioretention system performed better hydraulically than the smaller system. The results showed that more runoff routed through the larger system than the smaller one, and the maximum HRT of the larger system was substantially greater (by almost 2 days), then the maximum HRT in the smaller system. Based on the simulated HRT values, it was no surprise that the efficiency to achieve nitrification and denitrification was much better in the larger system, than in the smaller.

Overall, the EPA sized system achieved a nitrification rate of 84%, in comparison to only a rate 38% in the Sarasota sized system. The results from this study compare well to similar studies evaluating the performance of bioretention systems (for field-scale bioretention systems) [Ergas et al., 2010; Davis et al., 2006]. Both systems achieved the same rate of denitrification, 96% on average. However, the EPA sized ABC model reduced TN by as much as 87%, compared to the Sarasota sized system, which saw TN reductions of as much as 56%. The results from this research indicate that future design of these alternative bioretention systems should include careful planning to ensure that the area of the alternative bioretention system is close to the EPA's guidelines; 5-7% of the subcatchment area. Smaller alternative bioretention systems are not as efficient at achieving TN reductions, due to the reduced rate of nitrification.

Suggestions for Future Research

The ABC model is a first step in examining the potential of simulation software to be used in an effort to better estimate site-specific pre- vs. post-development alternative bioretention system performance. As the implementation of bioretention systems and other LID technologies increase in Florida, future applications of the ABC model should improve the model framework presented in this study. The following are some suggestions for future research:

- Conduct field-scale experiments of an alternative bioretention system used to treat stormwater runoff in southwest Florida. Compare field-scale removal efficiencies to SWMM-5 estimates.
- Include groundwater flow in future applications using the ABC model framework. The present model ignored groundwater flow. Groundwater influence is a major factor in quantity and quality treatment in these systems. Therefore, future research should incorporate groundwater data.

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Appendices

Appendix A: Runoff Quality Analyses for Events #1 & 2

TN Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.1. TN analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Concentration (mg/L)
TN	mean	1.48
TN	standard deviation	0.17
TN	medium	1.50
TN	maximum	1.70
TN	minimum	1.30
TN	Method Detection Limit	0.54

TN Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.2. TP analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Concentration (mg/l)
TP	mean	0.13
TP	standard deviation	0.02
TP	medium	0.12
TP	maximum	0.17
TP	minimum	0.11
TP	Method Detection Limit	0.07

pH Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.3. pH analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Units (0-14 pH units)
pH	mean	7.78
pH	standard deviation	0.19
pH	medium	7.74
pH	maximum	7.89
pH	minimum	7.53

Appendix A (Continued)

DO Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.4. DO analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Concentration (mg/L)
DO	mean	6.88
DO	standard deviation	0.29
DO	medium	6.87
DO	maximum	7.21
DO	minimum	6.55
DO	Method Detection Limit	0.90

Turbidity Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.5. Turbidity analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Units (NTU)
Turbidity	mean	1.51
Turbidity	standard deviation	0.17
Turbidity	medium	1.50
Turbidity	maximum	1.76
Turbidity	minimum	1.32
Turbidity	Method Detection Limit	0.52

Conductivity Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.6. Conductivity analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Result (µs/cm)
Conductivity	mean	1336.50
Conductivity	standard deviation	104.49
Conductivity	medium	1359.00
Conductivity	maximum	1421.00
Conductivity	minimum	1139.00
Conductivity	Method Detection Limit	328.11

Appendix A (Continued)

BOD Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.7. BOD analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Concentration (mg/L)
BOD	mean	4.20
BOD	standard deviation	0.34
BOD	medium	4.15
BOD	maximum	4.70
BOD	minimum	3.87
BOD	Method Detection Limit	1.07

TSS Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.8. TSS analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Concentration (mg/L)
TSS	mean	25.45
TSS	standard deviation	3.15
TSS	medium	25.40
TSS	maximum	28.67
TSS	minimum	22.17

VSS Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.9. VSS analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Concentration (mg/L)
VSS	mean	14.78
VSS	standard deviation	2.41
VSS	medium	15.83
VSS	maximum	16.27
VSS	minimum	11.17

Appendix A (Continued)

VSS Analysis for Field Event #1 & 2: Conducted on November 4th and December 11th, 2010

Table A.10. Total Coliform analysis of stormwater runoff at Venice East Blvd. site.

Analyte	Statistics	Counted (1/mL)	CFU/ 100 mL
CFU	mean	27.20	2720.00
CFU	standard deviation	4.71	470.93
CFU	medium	27.50	2750.00
CFU	maximum	36.00	3600.00
CFU	minimum	20.00	2000.00

Appendix B: Extra Tables

Long Term Rainfall Data

Table D.1. Comparison of long-term (1915-2010) rainfall data [adapted from PBS&J, 2010]

Month	**Mean (inches)**	**Maximum (inches)**	**Median (inches)**	**Minimum (inches)**	**2010 Rainfall**
January	2.28	8.09	1.82	0.00	2.76
February	2.63	9.29	2.35	0.01	2.40
March	2.96	10.14	2.25	0.13	7.21
April	2.43	10.52	1.99	0.00	2.93
May	3.05	10.11	2.55	0.20	1.56
June	7.61	22.45	6.94	2.22	5.69
July	8.25	16.05	7.95	2.45	5.70
August	8.59	19.08	7.73	2.37	11.22
September	7.75	18.63	7.25	3.27	4.68
October	3.32	10.90	2.42	0.00	4.43
November	1.86	6.71	1.39	0.00	2.29
December	2.02	9.29	1.49	0.00	1.65
Annual	52.57	151.26	46.13	10.65	52.52

Appendix C: SWMM-5 Input Parameters

Options

Flow units	CFS
Infiltration	Green Ampt
Flow Routing	Dynwave
Start date	6/3/1974
Start time	0:00:00
Report start date	6/3/1974
Report start time	0:00:00
End date	6/5/1974
End time	0:30:00
Sweep start	1-Jan
Sweep end	31-Dec
Dry days	10
Report step	0:30:00
Wet step	0:05:00
Dry step	1:00:00
Routing step	yes
Allow ponding	none
Inertial damping	None
Variable step	0.75
Lengthening step	0
Min surface area	0
Norm flow limited	Both
Skip steady state	none
Force main eq	D-W
Link offsets	Depth
Min-slope	0

Figure C.1. Options dialog box input parameters.

Evaporation

Type	Parameter
Constant	0
Dry only	No

Figure C.2. Evaporation input parameters.

Raingages

Rain	Rain Type	Time Interval	Snow Catch	Data Source
0.81 in. 1/13/74	intensity	0:30:00	1	Timeseries 1/13/74
0.60 in. 4/15/74	intensity	0:30:00	1	Timeseries 4/14/74
1.25 in. 6/17/74	intensity	0:30:00	1	Timeseries 6/17/74
1.92 in. 7/19/74	intensity	0:30:00	1	Timeseries 7/19/74
4.37 in. 9/18/74	intensity	0:30:00	1	Timeseries 9/18/74
0.14 in. 12/26/74	intensity	0:30:00	1	Timeseries 12/12/74

Figure C.3. Raingages input parameters.

Subcatchments

Name	Raingage	Outlet	Total Area	Percent Imperv	Width	Percent Slope	Curb Length	Snow Pack
Venice East Blvd. Street	varies	Inlet	58.39	41.8	163	2.7	0	

Figure C.4. Subcatchments input parameters.

Subareas

Subcatchment	N-Imper	N-Perv	S-Imperv	S-Perv	PctZero	RouteTo	PctRouted
Street	0.013	0.106	0.04	0.2	41.8	Outlet	

Figure C.5. Subareas input parameters.

Infiltration

Subcatchment	Suction	HydCon	IMDmax
Street	3	0.5	4

Figure C.6. Infiltration input parameters.

Outfalls

Name	Invert Elevation	Outfall	Tide Gate
Surface	0	Free	Yes

Figure C.7. Outfalls input parameters.

Storage Unit

Name	Invert Elev	Max Depth	Init. Depth	Storage Curve	Curve Parameters	Ponded area Sarasota	Ponded Area EPA
Inlet	2.99	10	0	Functional	1000	0	0
Pond Layer	2.83	1	0	Functional	1000	389.87	94
Inlet Down	0	0	0	Functional	1000	0	0
Media-Nitrif.	1.83	1.58	0	Functional	1000	615.94	80239.51
Media-Denit.	0.25	0.5	0	Functional	1000	195	25495.2
Trench	0.15	0.25	0	Functional	1000	97.47	0

Figure C.8. Storage unit input parameters

Conduits

Name	Inlet Node	Outlet Node	Length	Manning N	Inlet Offset	Outlet Offset	Init. Flow	Max Flow
1	Surface	Inlet Down	400	0.01	2	1	0	0

Figure C.9. Conduits input parameters.

Orifices

Name	Inlet Node	Outlet Node	Orifice Type	Crest Height	Disch. Coeff.	Flap Gate	Open/Close Time
PondIn	Inlet	PondLayer	Side	0	0.65	No	0
CurbLower	Inlet	Inlet Down	Side	0	0.65	No	0
FlowTo-Nit.	PondLayer	MediaLayer-Nit.	Side	0	0.65	No	0
FlowTo-Denit.	MediaLayer-Nit.	MediaLayer-Denit.	Side	0	0.65	No	0
MediaOut	MediaLayer-Denit.	Trench	Side	0	0.65	No	0

Figure C.10. Orifices input parameters.

Weirs

Name	Inlet Node	Outlet Node	Weir Type	Crest Height	Disch. Coeff.	Flap Gate	End Con.	End Coeff.
Overflow Weir	Trench	Inlet Down	V-notch	0	3.33	Yes	0	0

Figure C.11. Weirs input parameters.

Appendix C (Continued)

XSections

Link	Shape	Geom1	Geom2	Geom3	Geom4	Barrels
1	Circular	1	0	0	0	1
PondIn	Circular	2.83	0	0	0	0
CurbLower	Circular	3.25	0	0	0	0
FlowTo-Nit.	Circular	1.83	0	0	0	0
FlowTo-Denit	Circular	0.25	0	0	0	0
MediaOut	Circular	0.15	0	0	0	0
Overflow Weir	Circular	1.5	1	0	0	0

Figure C.12. XSections input parameters.

Pollutants

Name	Mass units	Rain Conc.	GW Conc.	I&I Conc.	Snow Only	Co-Pollutant	DWF Conc.
TKNi	mg/L	Input value	0	0	0	*	0
NO3i	mg/L	Input Value	0	0	0	TKNi	0
NO3	mg/L	Input Value	0	0	0	NO3i	0

Figure C.13. Pollutants input parameters.

Landuses

Name	Cleaning Interval	Fraction Avail.	Last Cleaned
Single Family Residential	0	0	0

Figure C.14. Landuses input parameters.

Washoff

Land Use	Pollutant	Function	Coeff. 1	Coeff. 2	Cleaning Effic.	BMP Effic.
Single Family Residential	TKNi	EMC	0.1	0	0	0
Single Family Residential	NO3i	EMC	0	0	0	0
Single Family Residential	NO3	EMC	0	0	0	0

Figure C.15. Washoff input parameters.

Appendix C (Continued)

Treatment

Treatment	Pollutant	Function
MediaLayer-Nitrification	TKNi	C= (TKNi)*exp(-0.81*HRT)
MediaLayer-Denitrification	NO3	C= (NO3i +R_TKNi)*exp(-2.5*HRT)

Figure C.16. Treatment input parameters.

Appendix D: SWMM-5 Water Quality Output Data

Quality Routing Results: analyses using the minimum concentrations

```
**************************          TKNi        NO3i         NO3
 Quality Routing Continuity         lbs         lbs         lbs
 **************************    ----------   ----------   ----------
 Dry Weather Inflow .......       0.000       0.000       0.000
 Wet Weather Inflow .......        0.761       0.005       0.005
 Groundwater Inflow .......       0.000       0.000       0.000
 RDII Inflow .............       0.000       0.000       0.000
 External Inflow ..........       0.000       0.000       0.000
 Internal Flooding ........       0.653       0.005       0.004
 External Outflow .........       0.000       0.000       0.000
 Mass Reacted ............       0.260       0.026       0.007
 Initial Stored Mass ......       0.000       0.000       0.000
 Final Stored Mass ........       0.000       0.000       0.000
 Continuity Error (%) .....      -19.946     -519.045     -129.052
```

Figure D.1. Simulation using minimum concentration in Sarasota sized ABC model for the 1/13/74 storm event.

```
**************************          TKNi        NO3i         NO3
 Quality Routing Continuity         lbs         lbs         lbs
 **************************    ----------   ----------   ----------
 Dry Weather Inflow .......       0.000       0.000       0.000
 Wet Weather Inflow .......        0.762       0.005       0.005
 Groundwater Inflow .......       0.000       0.000       0.000
 RDII Inflow .............       0.000       0.000       0.000
 External Inflow ..........       0.000       0.000       0.000
 Internal Flooding ........       0.648       0.005       0.004
 External Outflow .........       0.000       0.000       0.000
 Mass Reacted ............       0.966       0.110       0.006
 Initial Stored Mass ......       0.000       0.000       0.000
 Final Stored Mass ........       0.001       0.000       0.000
 Continuity Error (%) .....     -111.918    -2189.876     -107.867
```

Figure D.2. Simulation using minimum concentration in EPA sized ABC model for the 1/13/74 storm event.

Appendix D (Continued)

```
**************************        TKNi       NO3i       NO3
 Quality Routing Continuity       lbs        lbs        lbs
 **************************    ----------  ----------  ----------
 Dry Weather Inflow .......       0.000      0.000      0.000
 Wet Weather Inflow .......       0.551      0.004      0.004
 Groundwater Inflow .......       0.000      0.000      0.000
 RDII Inflow .............     0.000      0.000      0.000
 External Inflow ..........     0.000      0.000      0.000
 Internal Flooding ........     0.460      0.004      0.003
 External Outflow .........     0.000      0.000      0.000
 Mass Reacted ............      0.241      0.023      0.006
 Initial Stored Mass ......     0.000      0.000      0.000
 Final Stored Mass ........     0.000      0.000      0.000
 Continuity Error (%) .....    -27.268    -648.419    -155.467
```

Figure D.3. Simulation using minimum concentration in Sarasota sized ABC model for the 4/15/74 storm event.

```
**************************        TKNi       NO3i       NO3
 Quality Routing Continuity       lbs        lbs        lbs
 **************************    ----------  ----------  ----------
 Dry Weather Inflow .......       0.000      0.000      0.000
 Wet Weather Inflow .......       0.551      0.004      0.003
 Groundwater Inflow .......       0.000      0.000      0.000
 RDII Inflow .............     0.000      0.000      0.000
 External Inflow ..........     0.000      0.000      0.000
 Internal Flooding ........     0.462      0.004      0.002
 External Outflow .........     0.000      0.000      0.000
 Mass Reacted ............      0.861      0.085      0.005
 Initial Stored Mass ......     0.000      0.000      0.000
 Final Stored Mass ........     0.000      0.000      0.000
 Continuity Error (%) .....    -140.000    -2379.841    -122.735
```

Figure D.4. Simulation using minimum concentration in EPA sized ABC model for the 4/15/74 storm event.

Appendix D (Continued)

```
**************************          TKNi       NO3i        NO3
  Quality Routing Continuity        lbs        lbs        lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......        1.202        0.008        0.008
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............         0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........        1.082        0.008        0.007
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............         0.274        0.028        0.008
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.000        0.000        0.000
  Continuity Error (%) .....      -12.844     -348.307      -89.883
```

Figure D.5. Simulation using minimum concentration in Sarasota sized ABC model for the 6/17/74 storm event.

```
**************************          TKNi       NO3i        NO3
  Quality Routing Continuity        lbs        lbs        lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......        1.203        0.008        0.007
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............         0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........        0.983        0.008        0.006
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............         0.972        0.133        0.010
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.001        0.000        0.000
  Continuity Error (%) .....      -62.574    -1644.763     -123.126
```

Figure D.6. Simulation using minimum concentration in EPA sized ABC model for the 6/17/74 storm event.

Appendix D (Continued)

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......        0.000       0.000       0.000
  Wet Weather Inflow .......         1.873       0.013       0.013
  Groundwater Inflow .......        0.000       0.000       0.000
  RDII Inflow .............       0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       1.741       0.013       0.012
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............       0.309       0.032       0.010
  Initial Stored Mass ......      0.000       0.000       0.000
  Final Stored Mass ........       0.000       0.000       0.000
  Continuity Error (%) .....      -9.480     -251.968     -68.246
```

Figure D.7. Simulation using minimum concentration in Sarasota sized ABC model for the 7/19/74 storm event.

```
*************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......        0.000       0.000       0.000
  Wet Weather Inflow .......         1.874       0.013       0.011
  Groundwater Inflow .......        0.000       0.000       0.000
  RDII Inflow .............       0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       1.497       0.013       0.010
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............       1.239       0.188       0.019
  Initial Stored Mass ......      0.000       0.000       0.000
  Final Stored Mass ........       0.001       0.000       0.000
  Continuity Error (%) .....     -46.053    -1484.363    -159.169
```

Figure D.8. Simulation using minimum concentration in EPA sized ABC model for the 7/19/74 storm event.

Appendix D (Continued)

```
*************************        TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  *************************    ----------   ----------   ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......        4.323        0.030        0.030
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............        0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........        4.120        0.030        0.028
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............        0.498        0.053        0.017
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.001        0.000        0.000
  Continuity Error (%) .....       -6.844     -179.537      -53.690
```

Figure D.9. Simulation using minimum concentration in Sarasota sized ABC model for the 9/18/74 storm event.

```
*************************        TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  *************************    ----------   ----------   ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......        4.324        0.030        0.027
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............        0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........        3.487        0.029        0.025
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............        2.315        0.461        0.067
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.011        0.000        0.000
  Continuity Error (%) .....      -34.409    -1556.887     -242.549
```

Figure D.10. Simulation using minimum concentration in EPA sized ABC model for the 9/18/74 storm event.

```
**************************          TKNi        NO3i         NO3
  Quality Routing Continuity         lbs         lbs         lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......        0.090        0.000        0.000
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............         0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........        0.067        0.000        0.000
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............         0.111        0.006        0.001
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.000        0.000        0.000
  Continuity Error (%) .....      -98.686    -1473.505     -220.507
```

Figure D.11. Simulation using minimum concentration in Sarasota sized ABC model for the 12/26/74 storm event.

```
**************************          TKNi        NO3i         NO3
  Quality Routing Continuity         lbs         lbs         lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......        0.091        0.000        0.000
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............         0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........        0.068        0.000        0.000
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............         0.114        0.006        0.001
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.000        0.000        0.000
  Continuity Error (%) .....     -100.975    -1496.250     -226.824
```

Figure D.12. Simulation using minimum concentration in EPA sized ABC model for the 12/26/74 storm event.

Appendix D (Continued)

Quality Routing Results: analyses using the median concentrations

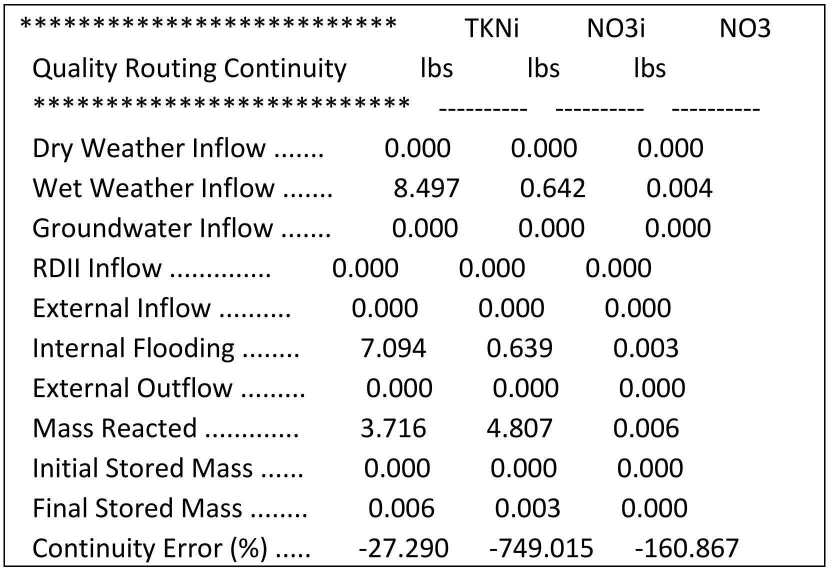
```
**************************        TKNi       NO3i        NO3
 Quality Routing Continuity       lbs        lbs        lbs
 **************************    ----------  ----------  ----------
 Dry Weather Inflow .......       0.000       0.000       0.000
 Wet Weather Inflow .......      11.740       0.887       0.005
 Groundwater Inflow .......       0.000       0.000       0.000
 RDII Inflow .............     0.000       0.000       0.000
 External Inflow ..........      0.000       0.000       0.000
 Internal Flooding ........     10.070       0.884       0.004
 External Outflow .........      0.000       0.000       0.000
 Mass Reacted .............      4.008       5.282       0.007
 Initial Stored Mass ......      0.000       0.000       0.000
 Final Stored Mass ........      0.006       0.003       0.000
 Continuity Error (%) .....    -19.964    -595.659    -132.470
```

Figure D.13. Simulation using median concentration in Sarasota sized ABC model for the 1/13/74 storm event.

```
**************************        TKNi       NO3i        NO3
 Quality Routing Continuity       lbs        lbs        lbs
 **************************    ----------  ----------  ----------
 Dry Weather Inflow .......       0.000       0.000       0.000
 Wet Weather Inflow .......      11.754       0.888       0.005
 Groundwater Inflow .......       0.000       0.000       0.000
 RDII Inflow .............     0.000       0.000       0.000
 External Inflow ..........      0.000       0.000       0.000
 Internal Flooding ........      9.996       0.886       0.004
 External Outflow .........      0.000       0.000       0.000
 Mass Reacted .............     14.906      19.887       0.006
 Initial Stored Mass ......      0.000       0.000       0.000
 Final Stored Mass ........      0.009       0.003       0.000
 Continuity Error (%) .....   -111.934   -2240.175    -110.546
```

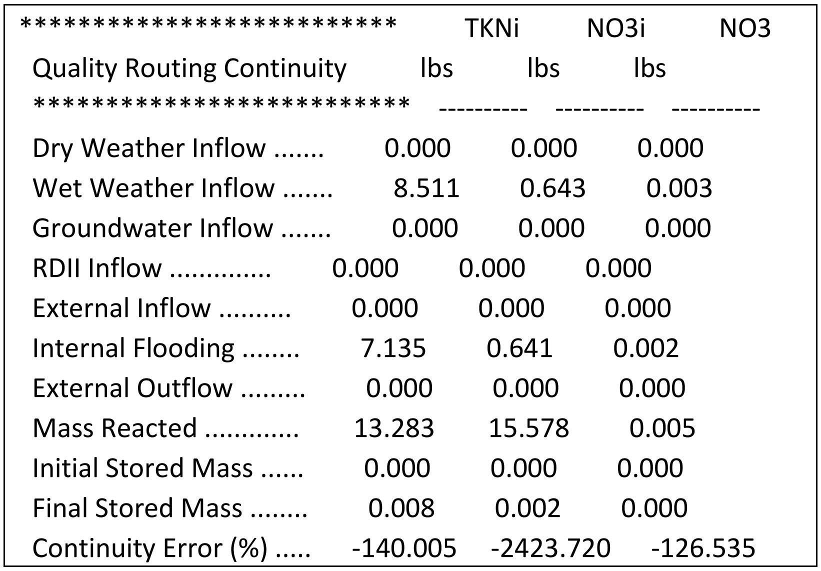
Figure D.14. Simulation using median concentration in EPA sized ABC model for the 1/13/74 storm event.

Appendix D (Continued)



```
**************************        TKNi       NO3i        NO3
  Quality Routing Continuity        lbs        lbs        lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......       8.497       0.642       0.004
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       7.094       0.639       0.003
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............       3.716       4.807       0.006
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.006       0.003       0.000
  Continuity Error (%) .....     -27.290    -749.015    -160.867
```

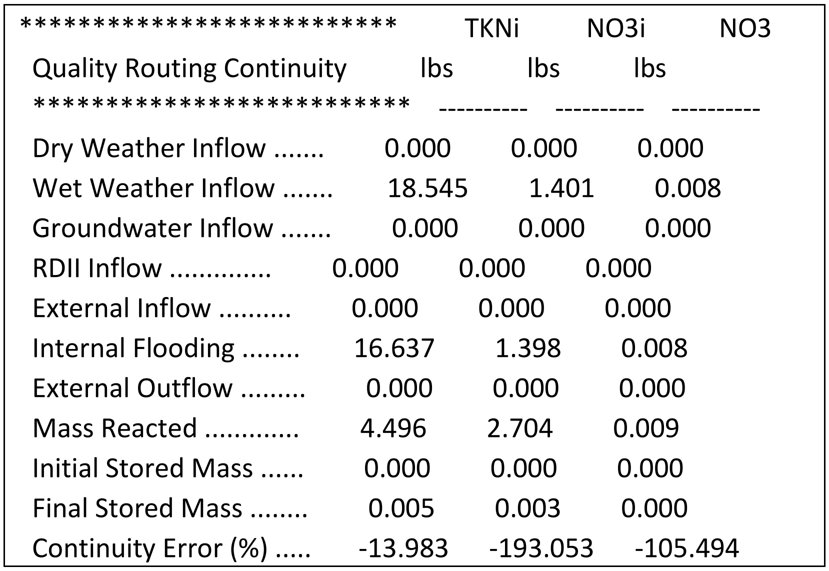
Figure D.15. Simulation using median concentration in Sarasota sized ABC model for the 4/15/74 storm event.



```
**************************        TKNi       NO3i        NO3
  Quality Routing Continuity        lbs        lbs        lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......       8.511       0.643       0.003
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       7.135       0.641       0.002
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............      13.283      15.578       0.005
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.008       0.002       0.000
  Continuity Error (%) .....    -140.005   -2423.720    -126.535
```

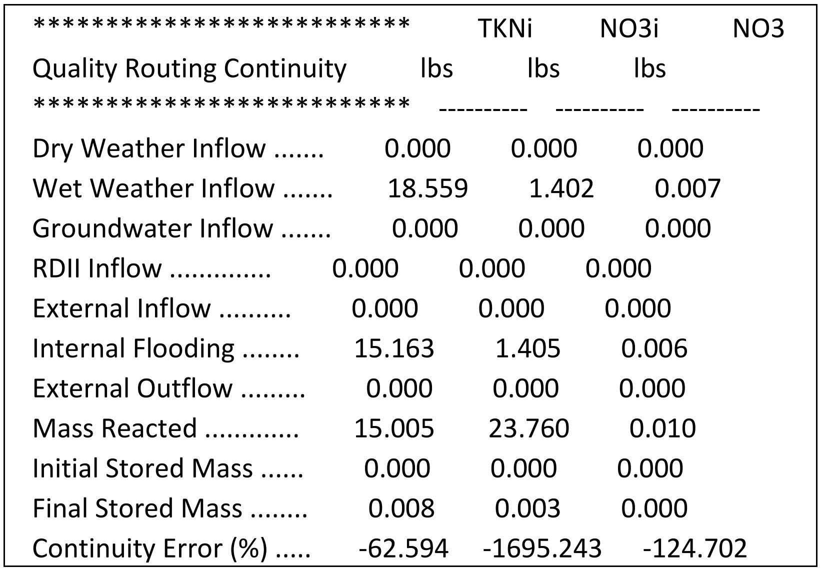
Figure D.16. Simulation using median concentration in EPA sized ABC model for the 4/15/74 storm event.

Appendix D (Continued)



```
*************************      TKNi       NO3i       NO3
 Quality Routing Continuity       lbs        lbs        lbs
 *************************   ----------  ----------  ----------
 Dry Weather Inflow .......      0.000      0.000      0.000
 Wet Weather Inflow .......      18.545      1.401      0.008
 Groundwater Inflow .......      0.000      0.000      0.000
 RDII Inflow .............      0.000      0.000      0.000
 External Inflow ..........      0.000      0.000      0.000
 Internal Flooding ........      16.637      1.398      0.008
 External Outflow .........      0.000      0.000      0.000
 Mass Reacted ............      4.496      2.704      0.009
 Initial Stored Mass ......      0.000      0.000      0.000
 Final Stored Mass ........      0.005      0.003      0.000
 Continuity Error (%) .....      -13.983    -193.053    -105.494
```

Figure D.17. Simulation using median concentration in Sarasota sized ABC model for the 6/17/74 storm event.



```
 *************************      TKNi       NO3i       NO3
 Quality Routing Continuity       lbs        lbs        lbs
 *************************   ----------  ----------  ----------
 Dry Weather Inflow .......      0.000      0.000      0.000
 Wet Weather Inflow .......      18.559      1.402      0.007
 Groundwater Inflow .......      0.000      0.000      0.000
 RDII Inflow .............      0.000      0.000      0.000
 External Inflow ..........      0.000      0.000      0.000
 Internal Flooding ........      15.163      1.405      0.006
 External Outflow .........      0.000      0.000      0.000
 Mass Reacted ............      15.005      23.760      0.010
 Initial Stored Mass ......      0.000      0.000      0.000
 Final Stored Mass ........      0.008      0.003      0.000
 Continuity Error (%) .....      -62.594    -1695.243    -124.702
```

Figure D.18. Simulation using median concentration in EPA sized ABC model for the 6/17/74 storm event.

Appendix D (Continued)

```
**************************        TKNi        NO3i        NO3
 Quality Routing Continuity        lbs        lbs        lbs
 **************************    ----------  ----------  ----------
 Dry Weather Inflow .......       0.000       0.000       0.000
 Wet Weather Inflow .......      28.899       2.183       0.013
 Groundwater Inflow .......       0.000       0.000       0.000
 RDII Inflow .............     0.000       0.000       0.000
 External Inflow ..........      0.000       0.000       0.000
 Internal Flooding ........      26.867       2.181       0.012
 External Outflow .........      0.000       0.000       0.000
 Mass Reacted .............      4.768       6.264       0.010
 Initial Stored Mass ......      0.000       0.000       0.000
 Final Stored Mass ........      0.007       0.003       0.000
 Continuity Error (%) .....     -9.488     -286.993     -69.424
```

Figure D.19. Simulation using median concentration in Sarasota sized ABC model for the 7/19/74 storm event.

```
**************************        TKNi        NO3i        NO3
 Quality Routing Continuity        lbs        lbs        lbs
 **************************    ----------  ----------  ----------
 Dry Weather Inflow .......       0.000       0.000       0.000
 Wet Weather Inflow .......      28.914       2.184       0.011
 Groundwater Inflow .......       0.000       0.000       0.000
 RDII Inflow .............     0.000       0.000       0.000
 External Inflow ..........      0.000       0.000       0.000
 Internal Flooding ........      23.103       2.183       0.010
 External Outflow .........      0.000       0.000       0.000
 Mass Reacted .............      19.120      33.337       0.020
 Initial Stored Mass ......      0.000       0.000       0.000
 Final Stored Mass ........      0.011       0.004       0.000
 Continuity Error (%) .....     -46.070    -1526.405    -160.199
```

Figure D.20. Simulation using median concentration in EPA sized ABC model for the 7/19/74 storm event.

```
**************************          TKNi        NO3i         NO3
  Quality Routing Continuity         lbs         lbs         lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......       66.694        5.038        0.030
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............         0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........       63.571        5.038        0.028
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............         7.682        9.745        0.017
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.009        0.003        0.000
  Continuity Error (%) .....       -6.848     -193.459      -54.250
```

Figure D.21. Simulation using median concentration in Sarasota sized ABC model for the 9/18/74 storm event.

```
**************************          TKNi        NO3i         NO3
  Quality Routing Continuity         lbs         lbs         lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......       66.714        5.040        0.027
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............         0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........       53.794        4.973        0.025
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............        35.719       79.793        0.067
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.163        0.068        0.000
  Continuity Error (%) .....      -34.419    -1583.250     -243.032
```

Figure D.22. Simulation using median concentration in EPA sized ABC model for the 9/18/74 storm event.

Appendix D (Continued)

```
**************************         TKNi        NO3i         NO3
 Quality Routing Continuity         lbs         lbs         lbs
 **************************    ----------   ----------   ----------
 Dry Weather Inflow .......       0.000        0.000        0.000
 Wet Weather Inflow .......        1.392        0.105        0.000
 Groundwater Inflow .......       0.000        0.000        0.000
 RDII Inflow .............       0.000        0.000        0.000
 External Inflow ..........       0.000        0.000        0.000
 Internal Flooding ........       1.042        0.102        0.000
 External Outflow .........       0.000        0.000        0.000
 Mass Reacted ............       1.718        1.955        0.001
 Initial Stored Mass ......       0.000        0.000        0.000
 Final Stored Mass ........       0.005        0.002        0.000
 Continuity Error (%) .....      -98.701     -1863.335     -256.266
```

Figure D.23. Simulation using median concentration in Sarasota sized ABC model for the 12/26/74 storm event.

```
**************************         TKNi        NO3i         NO3
 Quality Routing Continuity         lbs         lbs         lbs
 **************************    ----------   ----------   ----------
 Dry Weather Inflow .......       0.000        0.000        0.000
 Wet Weather Inflow .......        1.403        0.106        0.000
 Groundwater Inflow .......       0.000        0.000        0.000
 RDII Inflow .............       0.000        0.000        0.000
 External Inflow ..........       0.000        0.000        0.000
 Internal Flooding ........       1.050        0.104        0.000
 External Outflow .........       0.000        0.000        0.000
 Mass Reacted ............       1.766        2.073        0.001
 Initial Stored Mass ......       0.000        0.000        0.000
 Final Stored Mass ........       0.004        0.002        0.000
 Continuity Error (%) .....     -100.992     -1960.508     -267.090
```

Figure D.24. Simulation using median concentration in EPA sized ABC model for the 12/26/74 storm event.

Appendix D (Continued)

Quality Routing Results: analyses using the maximum concentrations

```
**************************         TKNi       NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......      35.945       3.784       0.005
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............       0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........      30.831       3.772       0.004
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............       12.270      22.551       0.007
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.019       0.012       0.000
  Continuity Error (%) .....     -19.965    -595.994    -135.622
```

Figure D.25. Simulation using maximum concentration in Sarasota sized ABC model for the 1/13/74 storm event.

```
**************************         TKNi       NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......      35.988       3.788       0.005
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............       0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........      30.604       3.782       0.004
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............       45.640      84.868       0.006
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.027       0.011       0.000
  Continuity Error (%) .....    -111.934   -2240.395    -111.680
```

Figure D.26. Simulation using maximum concentration in EPA sized ABC model for the 1/13/74 storm event.

Appendix D (Continued)

```
**************************        TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......      26.017       2.739       0.004
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........      21.720       2.727       0.003
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............       11.378      20.524       0.006
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.019       0.012       0.000
  Continuity Error (%) .....     -27.291    -749.446    -165.146
```

Figure D.27. Simulation using maximum concentration in Sarasota sized ABC model for the 4/15/74 storm event.

```
*************************        TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------   ----------   ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......      26.058       2.743       0.003
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........      21.846       2.736       0.002
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............       40.670      66.483       0.005
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.023       0.010       0.000
  Continuity Error (%) .....    -140.005   -2423.908    -128.069
```

Figure D.28. Simulation using maximum concentration in EPA sized ABC model for the 4/15/74 storm event.

Appendix D (Continued)

```
**************************       TKNi       NO3i       NO3
 Quality Routing Continuity       lbs        lbs        lbs
 **************************   ----------  ----------  ----------
 Dry Weather Inflow .......       0.000       0.000       0.000
 Wet Weather Inflow .......      56.779       5.977       0.008
 Groundwater Inflow .......       0.000       0.000       0.000
 RDII Inflow .............     0.000       0.000       0.000
 External Inflow ..........      0.000       0.000       0.000
 Internal Flooding ........      51.128       5.965       0.007
 External Outflow .........       0.000       0.000       0.000
 Mass Reacted ............      12.932      23.994       0.008
 Initial Stored Mass ......       0.000       0.000       0.000
 Final Stored Mass ........       0.019       0.012       0.000
 Continuity Error (%) .....     -12.857    -401.448     -93.732
```

Figure D.29. Simulation using maximum concentration in Sarasota sized ABC model for the 6/17/74 storm event.

```
**************************       TKNi       NO3i       NO3
 Quality Routing Continuity       lbs        lbs        lbs
 **************************   ----------  ----------  ----------
 Dry Weather Inflow .......       0.000       0.000       0.000
 Wet Weather Inflow .......      56.822       5.982       0.007
 Groundwater Inflow .......       0.000       0.000       0.000
 RDII Inflow .............     0.000       0.000       0.000
 External Inflow ..........      0.000       0.000       0.000
 Internal Flooding ........      46.425       5.993       0.006
 External Outflow .........       0.000       0.000       0.000
 Mass Reacted ............      45.941     101.391       0.010
 Initial Stored Mass ......       0.000       0.000       0.000
 Final Stored Mass ........       0.025       0.012       0.000
 Continuity Error (%) .....     -62.595   -1695.467    -125.356
```

Figure D.30. Simulation using maximum concentration in EPA sized ABC model for the 6/17/74 storm event.

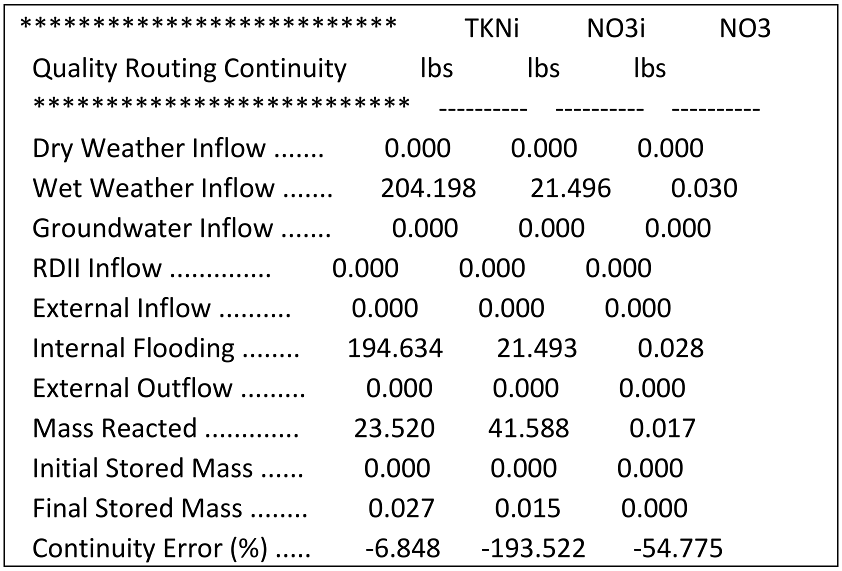
Appendix D (Continued)

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......        0.000       0.000       0.000
  Wet Weather Inflow .......        88.479      9.314       0.013
  Groundwater Inflow .......        0.000       0.000       0.000
  RDII Inflow .............     0.000       0.000       0.000
  External Inflow ..........        0.000       0.000       0.000
  Internal Flooding ........        82.257      9.307       0.012
  External Outflow .........        0.000       0.000       0.000
  Mass Reacted ............         14.597      26.740      0.010
  Initial Stored Mass ......        0.000       0.000       0.000
  Final Stored Mass ........        0.020       0.012       0.000
  Continuity Error (%) .....        -9.489      -287.150    -70.488
```

Figure D.31. Simulation using maximum concentration in Sarasota sized ABC model for the 7/19/74 storm event.

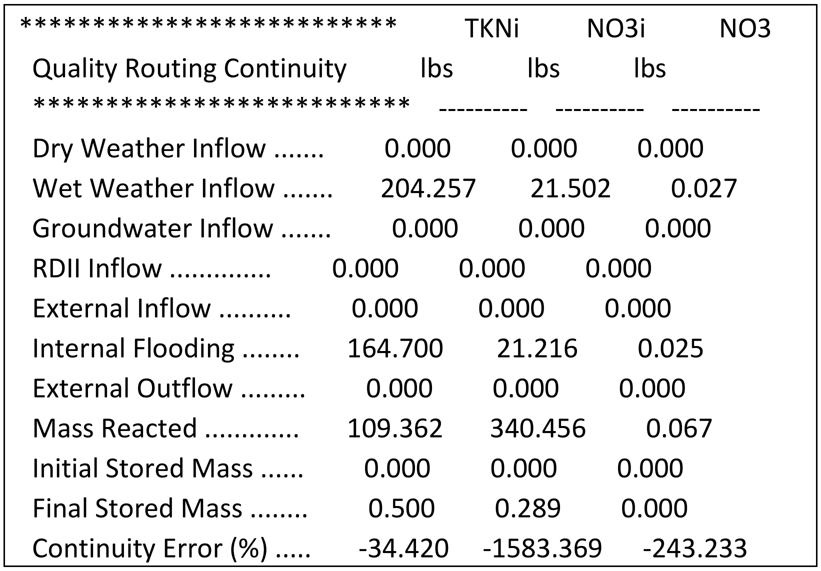
```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......        0.000       0.000       0.000
  Wet Weather Inflow .......        88.525      9.319       0.011
  Groundwater Inflow .......        0.000       0.000       0.000
  RDII Inflow .............     0.000       0.000       0.000
  External Inflow ..........        0.000       0.000       0.000
  Internal Flooding ........        70.736      9.313       0.010
  External Outflow .........        0.000       0.000       0.000
  Mass Reacted ............         58.541      142.251     0.020
  Initial Stored Mass ......        0.000       0.000       0.000
  Final Stored Mass ........        0.032       0.016       0.000
  Continuity Error (%) .....        -46.071     -1526.593   -160.628
```

Figure D.32. Simulation using maximum concentration in EPA sized ABC model for the 7/19/74 storm event.



```
**************************        TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************   ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......     204.198      21.496       0.030
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............    0.000       0.000       0.000
  External Inflow ..........     0.000       0.000       0.000
  Internal Flooding ........     194.634      21.493       0.028
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............      23.520      41.588       0.017
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.027       0.015       0.000
  Continuity Error (%) .....      -6.848    -193.522     -54.775
```

Figure D.33. Simulation using maximum concentration in Sarasota sized ABC model for the 9/18/74 storm event.



```
**************************        TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************   ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......     204.257      21.502       0.027
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............    0.000       0.000       0.000
  External Inflow ..........     0.000       0.000       0.000
  Internal Flooding ........     164.700      21.216       0.025
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............     109.362     340.456       0.067
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.500       0.289       0.000
  Continuity Error (%) .....     -34.420   -1583.369    -243.233
```

Figure D.34. Simulation using maximum concentration in EPA sized ABC model for the 9/18/74 storm event.

Appendix D (Continued)

```
**************************         TKNi        NO3i         NO3
  Quality Routing Continuity         lbs         lbs         lbs
  **************************    ----------    ----------    ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......        4.261        0.448        0.000
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............       0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........        3.192        0.438        0.000
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............        5.259        8.360        0.001
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.016        0.011        0.000
  Continuity Error (%) .....      -98.702     -1864.467     -271.730
```

Figure D.35. Simulation using maximum concentration in Sarasota sized ABC model for the 12/26/74 storm event.

```
**************************         TKNi        NO3i         NO3
  Quality Routing Continuity         lbs         lbs         lbs
  **************************    ----------    ----------    ----------
  Dry Weather Inflow .......        0.000        0.000        0.000
  Wet Weather Inflow .......        4.295        0.452        0.000
  Groundwater Inflow .......        0.000        0.000        0.000
  RDII Inflow .............       0.000        0.000        0.000
  External Inflow ..........        0.000        0.000        0.000
  Internal Flooding ........        3.214        0.443        0.000
  External Outflow .........        0.000        0.000        0.000
  Mass Reacted ............        5.407        8.866        0.001
  Initial Stored Mass ......        0.000        0.000        0.000
  Final Stored Mass ........        0.012        0.009        0.000
  Continuity Error (%) .....     -100.992     -1961.845     -283.809
```

Figure D.36. Simulation using maximum concentration in EPA sized ABC model for the 12/26/74 storm event.

Appendix D (Continued)

Quality Routing Results: analyses using the analyzed concentrations

```
**************************        TKNi        NO3i
NO3
  Quality Routing Continuity        lbs        lbs        lbs
  **************************    ----------    ----------    -------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......       6.156       3.112       0.005
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............       0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       5.244       3.102       0.005
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............       2.231       8.924       0.008
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.003       0.010       0.000
  Continuity Error (%) .....     -21.477     -286.766    -
154.558
```

Figure D.37. Simulation using analyzed concentration in Sarasota sized ABC model for the 1/13/74 storm event.

```
**************************        TKNi        NO3i        NO3
  Quality Routing Continuity        lbs        lbs        lbs
  **************************    ----------    ----------    ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......       6.163       3.116       0.005
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............       0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       5.241       3.111       0.004
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............       7.816      69.800       0.006
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.005       0.009       0.000
  Continuity Error (%) .....    -111.933    -2240.380    -110.533
```

Figure D.38. Simulation using analyzed concentration in EPA sized ABC model for the 1/13/74 storm event.

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......        4.456       2.252       0.004
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............      0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       3.720       2.243       0.003
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............        1.948      16.880       0.006
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........        0.003       0.010       0.000
  Continuity Error (%) .....      -27.289     -749.418     -161.013
```

Figure D.39. Simulation using analyzed concentration in Sarasota sized ABC model for the 4/15/74 storm event.

```
**************************          TKNi        NO3i         NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......        4.463       2.256       0.003
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............      0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       3.678       2.250       0.002
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted ............        7.270      26.310       0.005
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........        0.003       0.008       0.000
  Continuity Error (%) .....     -145.413    -1166.363    -136.526
```

Figure D.40. Simulation using analyzed concentration in EPA sized ABC model for the 4/15/74 storm event.

Appendix D (Continued)

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......       9.724       4.916       0.008
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       8.756       4.906       0.007
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............       2.215      19.734       0.008
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.003       0.010       0.000
  Continuity Error (%) .....     -12.855    -401.433     -92.287
```

Figure D.41. Simulation using analyzed concentration in Sarasota sized ABC model for the 6/17/74 storm event.

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......       9.732       4.920       0.007
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       7.951       4.929       0.006
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............       7.868      83.390       0.010
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.004       0.010       0.000
  Continuity Error (%) .....     -62.593   -1695.452    -124.738
```

Figure D.42. Simulation using analyzed concentration in EPA sized ABC model for the 6/17/74 storm event.

Appendix D (Continued)

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......      15.153       7.661       0.013
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........      14.088       7.655       0.012
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............       2.500      21.992       0.010
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.003       0.010       0.000
  Continuity Error (%) .....      -9.488    -287.139     -69.718
```

Figure D.43. Simulation using analyzed concentration in Sarasota sized ABC model for the 7/19/74 storm event.

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......      15.161       7.664       0.011
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........      12.114       7.660       0.010
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............      10.026     116.996       0.020
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.006       0.013       0.000
  Continuity Error (%) .....     -46.069   -1526.581    -160.183
```

Figure D.44. Simulation using analyzed concentration in EPA sized ABC model for the 7/19/74 storm event.

Appendix D (Continued)

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......        0.000       0.000       0.000
  Wet Weather Inflow .......       34.972      17.680       0.030
  Groundwater Inflow .......        0.000       0.000       0.000
  RDII Inflow .............     0.000       0.000       0.000
  External Inflow ..........      0.000       0.000       0.000
  Internal Flooding ........     33.334      17.677       0.028
  External Outflow .........      0.000       0.000       0.000
  Mass Reacted ............       4.028      34.204       0.017
  Initial Stored Mass ......      0.000       0.000       0.000
  Final Stored Mass ........      0.005       0.012       0.000
  Continuity Error (%) .....     -6.847    -193.517     -54.441
```

Figure D.45. Simulation using analyzed concentration in Sarasota sized ABC model for the 9/18/74 storm event.

```
**************************          TKNi        NO3i        NO3
  Quality Routing Continuity        lbs         lbs         lbs
  **************************    ----------  ----------  ----------
  Dry Weather Inflow .......        0.000       0.000       0.000
  Wet Weather Inflow .......       34.982      17.685       0.027
  Groundwater Inflow .......        0.000       0.000       0.000
  RDII Inflow .............     0.000       0.000       0.000
  External Inflow ..........      0.000       0.000       0.000
  Internal Flooding ........     28.207      17.449       0.025
  External Outflow .........      0.000       0.000       0.000
  Mass Reacted ............      18.729     280.012       0.067
  Initial Stored Mass ......      0.000       0.000       0.000
  Final Stored Mass ........      0.086       0.237       0.000
  Continuity Error (%) .....    -34.419   -1583.361    -243.008
```

Figure D.46. Simulation using analyzed concentration in EPA sized ABC model for the 9/18/74 storm event.

Appendix D (Continued)

```
**************************        TKNi       NO3i       NO3
  Quality Routing Continuity        lbs        lbs        lbs
  **************************   ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......       0.730       0.369       0.000
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       0.546       0.360       0.000
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............       0.901       6.875       0.001
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.003       0.009       0.000
  Continuity Error (%) .....     -98.700   -1864.393    -254.510
```

Figure D.47. Simulation using analyzed concentration in Sarasota sized ABC model for the 12/26/74 storm event.

```
**************************        TKNi       NO3i        NO3
  Quality Routing Continuity        lbs        lbs        lbs
  **************************   ----------  ----------  ----------
  Dry Weather Inflow .......       0.000       0.000       0.000
  Wet Weather Inflow .......       0.735       0.372       0.000
  Groundwater Inflow .......       0.000       0.000       0.000
  RDII Inflow .............        0.000       0.000       0.000
  External Inflow ..........       0.000       0.000       0.000
  Internal Flooding ........       0.550       0.364       0.000
  External Outflow .........       0.000       0.000       0.000
  Mass Reacted .............       0.926       7.291       0.001
  Initial Stored Mass ......       0.000       0.000       0.000
  Final Stored Mass ........       0.002       0.007       0.000
  Continuity Error (%) .....    -100.991   -1961.757    -265.172
```

Figure D.48. Simulation using analyzed concentration in EPA sized ABC model for the 12/26/74 storm event.

About the Author

Michelle Masi was born in Florida and earned her Bachelor of Science in Environmental Science from the University of South Florida. Academically, Michelle has gained an interdisciplinary skill set by taking courses in public health, water resources, environmental sciences, statistics and experimental design. Her research experience includes the development of a stochastic, age-based population model to assess Florida manatee population dynamics at the Florida Fish & Wildlife Research Institute. She has worked as a Environmental Engineer for the Florida Department of Environmental Protection, reviewing engineer drawings and applications for the development and repair of municipal water and wastewater systems. Michelle was recently awarded an S_STEM scholarship for academically talented graduate students from the College Engineering’s Department of Civil and Environmental Engineering.