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Innovating Green Stormwater Infrastructure for Nutrient Management: Long-Term Field and Modeling Studies of Conventional and Modified Denitrifying Bioretention Systems

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Innovating Green Stormwater Infrastructure for Nutrient Management: Long-Term Field and Modeling Studies of Conventional and Modified Denitrifying Bioretention Systems

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Environmental Engineering Department of Civil and Environmental Engineering College of Engineering University of South Florida

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Dedication

To my family! The Lopez, Ponnada, and Velasquez family. To my parents, Octavio Lopez and Maria Clemencia Velasquez, for their upbringing and everything they taught me including my faith in God. For all their hard work so that I could get the best education possible, one they did not have the opportunity to get, for teaching me the value of higher education, and introducing me first to the idea of obtaining a Ph.D. To my husband, Veneel Kumar Ponnada, for his love, for believing in me, and supporting me to follow my dreams; and to my daughter, Estelle Aishwarya Ponnada, for teaching me a new meaning of love and bringing me such happiness and joy during my Ph.D. journey. Los quiero mucho!

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Abstract

Urban stormwater and nutrient management are increasingly important topics to address globally, as coastal urbanization increases, disturbing the natural landscape, hydrology, and water quality. Untreated urban stormwater runoff carries pollutants that enter our waterways, such as rivers and marine environments, which serve as drinking water sources, recreational sites, and locations for economic livelihood. One pollutant and nutrient of concern for water quality is reactive nitrogen (N). Since pre-industrial time, reactive nitrogen has doubled from human activity. When found in excess in waterways, nitrogen causes an overabundant growth of algae, which can result in eutrophic and hypoxic conditions, impacting ecosystems, human health, and the economy. For this reason, managing the nitrogen cycle, designing a future without pollution, and creating healthy resilient cities have become grand challenges in the 21st century, as listed by the U.S. National Academy of Engineering and by the National Academies of Sciences, Engineering, and Medicine.

Green stormwater infrastructure is a suite of low impact development technologies and best management practices that can be applied strategically throughout a watershed to capture stormwater and reduce pollutants from urban runoff to natural waterways. One such technology increasingly being implemented is bioretention, a structural low impact development technology. Bioretention systems consist of a shallow depression with a planting bed and a series of permeable layers where the water that passes is filtered and treated. However, conventional bioretention systems are not designed specifically to remove or recover dissolved nitrogen species found in
stormwater. They have poor and inconsistent nitrogen removal, especially for nitrate (NO$_3^-$), which can be exported from conventional systems.

Nitrogen removal in a bioretention system can be improved by modifying the conventional system to promote biological nitrogen removal processes. Denitrification, the reduction of NO$_3^-$ to inert gaseous nitrogen (N$_2$), can be enhanced with the inclusion of an internal water storage zone (IWSZ) at the bottom of a bioretention system that contains an electron donor (e.g., an organic carbon source from wood chips). In modified bioretention systems reactive nitrogen is removed from the water and returned to the atmosphere. Prior studies have shown that the use of an IWSZ with a carbon source resulted in total nitrogen removal efficiencies greater than 88% under laboratory conditions. However, there have not been previous long-term field studies conducted on modified denitrifying bioretention systems for treating stormwater runoff assessing their continuous performance and stability.

Two bioretention systems, a conventional and a modified design, were installed side-by-side using locally available materials. The field-scale site is located in East Tampa in the property of a community partner, the Corporation to Develop Communities of Tampa, Inc. The bioretention systems were monitored for four years, with experiments conducted in years three and four. The results from simulated storm events in the field demonstrate that the biological and chemical processes that occur within the modified bioretention system significantly improve nitrogen removal. The modified system successfully removed over 75% of total N (TN) while the conventional system removed approximately 40%. Hydraulic loading rate had the most significant impact on nitrogen removal efficiency in the modified system, greater than the addition of plants or increased antecedent dry conditions. Greater NO$_3^-$ removal efficiencies were observed when the hydraulic loading rate was the lowest pertaining to a longer hydraulic retention time of the
stormwater in the IWSZ. For the conventional system, the addition of plants contributed to greater removal of NO$_3^-$ than the lowest hydraulic loading rate.

With the experimental data from the field, tracer studies, denitrification kinetic data from other studies employing the same media used in the IWSZ of this study, and rainfall data, a model for sub-tropical regions, such as Florida, was created for modified bioretention systems. The model uses local rainfall data and an event mean N concentration typical for the specific land use where the bioretention system is being placed to determine an annual N load for a specified impervious area. Rainfall data were analyzed to determine the frequency distribution of rain event depths, duration, and antecedent dry periods. Adequate detention time within the IWSZ is crucial for the design and performance of modified denitrifying bioretention systems, as concluded from the field experiments. The model results can be used to guide the sizing of modified bioretention systems by indicating the N removal efficiency of a system and identifying if annual N removal goals can be met for conditions of a site. Considering the local climate conditions in the design, practitioners can more accurately aim to meet not only hydrologic goals, but also water quality goals; which can also allow policy makers to provide incentives or credits when these are met.

Installing effectively designed bioretention systems has the potential to improve the water quality of watersheds in the long term. This type of research also provided and continues to provide an ongoing opportunity to engage with residents, urban planners, engineers, and government officials around the topic of stormwater and adopting green infrastructure. Bioretention systems can be installed not only as a stormwater and nitrogen control measure but also as a way to beautify and add more green spaces to communities.

This dissertation research occurred as part of service learning activities taking place within the community were the two bioretention cells were installed. Green infrastructure research was
conducted in collaboration with a community partner that actively involved members of the community; thus, providing mutually beneficial experiences for the researcher and the community, through co-learning and capacity-building. These experiences were recorded and reflected on based on six qualities identified for a service-learning project (i.e., integrative, reflective, contextualized, strength-based, reciprocal, and lifelong).
Chapter 1: Introduction

1.1 Background and Motivation

Urbanization in coastal cities has continued to increase over the several past decades. For example, from 1980 to 2003 Florida lead all U.S. states with a 75% increase in coastal population growth (NOAA, 2004). One such example of a Florida coastal region experiencing population growth is the Tampa Bay Metro Area (Tampa, St. Petersburg, Clearwater). From the year 2000 to 2007, it saw a growth from 3.4 million to 4 million residents (Tampa Bay Business Journal, 2007). In 2018, the Tampa area grew by 51,000 residents, coming in at number nine nationally for the largest increase in population (Associated Press, 2019). This phenomenon increases built infrastructure, reduces the area of pervious surfaces, infiltration rates, and prevents groundwater recharge; thereby, altering natural runoff pathways and increasing urban stormwater runoff carrying pollutants that can severely impact coastal water quality.

One pollutant of concern for water quality in coastal cities is reactive nitrogen (Nr), defined by the U.S Environmental Protection Agency (USEPA) as “all biologically active, chemically reactive, and radiatively active nitrogen compounds in the atmosphere and biosphere of the earth, in contrast to non-reactive gaseous N₂” (SAB, 2011). Nutrients such as nitrogen (N) and phosphorus (P), although vital for life on Earth, when found in excess in a natural body of water, may impair these systems with algal growth and eutrophication (Bartsch, 1971; Mihelcic and Zimmerman, 2014). This in turn causes a reduction to light penetration, sea grass mortality in coastal areas, and decreased levels of dissolved oxygen, resulting in hypoxia and anoxic
conditions. In the U.S., much of the east coast and Gulf of Mexico coast is affected by eutrophication and hypoxia leading to dead zones, with the number doubling worldwide every decade since the 1960’s (WRI, 2012; Diaz and Rosenberg, 2008). For this and other reasons, managing the N cycle has been listed as a Grand Challenge by the U.S. National Academy of Engineering (NAE, 2008) and recognized as having harmful environmental effects by the United Nations Environment Programme (UNEP, 2007).

As part of the Clean Water Act, the USEPA issues a list of impaired waters for all the 50 states, territories, and the District of Columbia. Nutrients are the second largest cause of impairment of the US waters impacting 7,917 reported water bodies as of August 2015 (with pathogens as the first cause impacting 10,887 water bodies). Florida came in fourth place with 2,292 impaired water bodies (USEPA, 2015a). Many of the impaired water bodies are attributed to non-point sources such as “Urban-Related Runoff/Stormwater” (Butcher, 2014; LeFevre, 2014; USEPA, 2015a).

The impact of stormwater has many ramifications on an urban environment. When properly managed, stormwater can serve as a resource (NASEM, 2019). For example, rainwater can be harvested for non-potable uses, such as flushing toilets, irrigation, or car washing. Stormwater can be infiltrated to recharge aquifers and diminish the stresses of over pumping. When stormwater is managed so that it is kept out of combined sewers, wastewater treatment facilities are able to maintain more steady flow rates and pollutant concentrations, resulting in improved performance (NASEM, 2019). In China the concept of “sponge city” and “sponge city facilities” has moved forward as a sponge city construction initiative to help solve increasing water related problems, such as flash floods, in cities which in recent years have resulted in substantial economic losses and even human casualties (Ding et al., 2019).
For this reason, green stormwater infrastructure has gained traction in recent years as a more sustainable alternative to manage stormwater. The main goal of green infrastructure is to slow, retain, and treat stormwater runoff close to the source using “green” and locally sourced materials such as plants, sand, gravel, and landscape rocks to provide natural features (BenDor et al., 2018). Green infrastructure encapsulates a suite of low-impact development technologies (LIDs) such as rainwater harvesting, green roofs, rain gardens, vegetated swales, bioretention systems, permeable pavers or asphalt, and urban tree corridors. LIDs aim to mimic the natural pre-development hydrology of an area by working with the landscape, maintaining natural drainage courses, and reducing imperviousness (PGC, 1999). Whereas conventional approaches to manage stormwater and reduce flooding in cities include combined sewer overflows and separate storm sewer systems, considered as grey infrastructure. In the City of Tampa, ditches, drainage canals and retention ponds (both wet and dry), and storm drains with outfalls to the Hillsborough river are the most common stormwater management systems which are designed mainly to reduce flooding (Tampa, 2015).

In addition to the reduction of runoff pollution and peak flows, there are other benefits attributed to green infrastructure. Some of these include improved aesthetics, improved economic value to properties, and increased biodiversity, added green spaces and recreation opportunities, educational opportunities, reduced urban heat island effects, and ecosystem services that result in human well-being (BenDor et al., 2018; Wendel et al., 2011). Yet, these benefits are not always considered when planning and selecting between green and gray stormwater infrastructure.

A type of LID technology for attenuating peak flows and improving water quality are bioretention systems, commonly referred to as “rain gardens” or “bioswales,” for their similarities in appearance and construction (Davis et al., 2009; Mihelcic and Zimmerman, 2014). Bioretention
systems are shallow depressions, with a planting bed and a series of permeable layers, where the stormwater is treated. They are efficient at removing solids and organics from stormwater runoff (Ergas et al., 2010). However, one of the issues with conventional bioretention systems is the difficulty in obtaining consistent N removal rates especially for nitrate (NO$_3^-$-N), as seen by the large variability of nutrient removal efficiencies from one design to another (Collins et al., 2010; Ahiablame et al., 2012). Modifying bioretention systems to include a denitrification layer, referred to as an internal water storage zone (IWSZ) containing an electron donor improved N removal efficiency in laboratory studies close to 100% (Lynn et al., 2015; LeFevre et al., 2014).

This research focused on testing a lined bioretention system design with an IWSZ that contains eucalyptus woodchips that was previously studied in the laboratory, to remove TN at full scale in an urban field location. This was a first demonstration study of its kind under southwest central Florida environmental conditions with humid subtropical weather, heavy wet summer months and dry winter months, well-drained sandy soils overlying porous limestone, and a relatively shallow water table (FDEP, 2015). In addition, bioretention design and media utilized is vital to the efficiency of N removal. Furthermore, design guidelines via the use of a simple model calibrated and validated with field data will assist designers in sizing modified bioretention systems optimized for nitrogen removal.

1.2 Overall Goal and Objectives

The overall goal of this research is to support improved management of nutrients in stormwater by advancing the current knowledge of bioretention systems used to enhance N removal at the field-scale level. The specific research questions (RQ) are:
• RQ1. What are the prior knowledge and research gaps in the literature pertaining to denitrifying wood chip bioreactors? A critical review of the literature was completed on denitrifying bioreactors employing wood chip media used to manage residential non-point sources of nitrogen. This was done specifically for applications to stormwater runoff and on-site wastewater treatment.

• RQ2. Is total N removal performance observed in the field greater in a modified lined denitrifying bioretention system when compared with a conventional bioretention system? To answer this question the research statistically evaluated and compared N removal performance of a conventional and modified bioretention system in the field under: 1) varying hydraulic loading rates, 2) antecedent dry conditions, and 3) unplanted and planted conditions, while maintaining constant influent concentrations from simulated storm event experiments doused with synthetic stormwater.

• RQ3. How can stormwater management models be improved to more accurately estimate N removal for modified bioretention systems in urban locations? To address this research question, a model was developed that is based on empirical evidence of the local climate (rainfall conditions and antecedent dry periods) and the denitrification kinetics expected in a modified bioremediation systems employing an IWSZ that can be implemented as an add-in to established modeling software’s such as SWMM. The field results are compared with results from the model to calibrate and validate the model and demonstrate the model can be used to design and assess field based bioretention systems for N removal.

• RQ4. How can local stormwater practitioners design modified bioretention systems to address the nitrogen removal efficiencies needed in a local watershed to improve water quality conditions? To address this question, the model results are used to provide design
recommendations for sizing IWSZ of modified bioretention systems for specific sites to reach target N removal goals for current and future climatic conditions by using the validated model.

- RQ5. How can graduate research associated with stormwater and green infrastructure engage a local community through service learning activities? To address this question, the researcher integrated service learning activities within the community where the field research site was located. The researcher engaged middle and high school students who were associated with a Youth Leadership Movement group and adults from the Tampa Vocational Institute, both programs of the community partner, the Corporation to Develop Communities of Tampa, Inc.

This dissertation is divided into six chapters. Chapter 1 introduces the research, Chapter 2 addresses RQ1, Chapter 3 addresses RQ2, and Chapter 4 addresses RQ3 and RQ4, Chapter 5 addresses RQ 5, and Chapter 6 provides conclusions and recommendations for future research.
Chapter 2: Application of Denitrifying Wood Chip Bioreactors for Management of Residential Non-Point Sources of Nitrogen

2.1 Abstract

Two important and large non-point sources of nitrogen in residential areas that adversely affect water quality are stormwater runoff and effluent from on-site treatment systems. These sources are challenging to control due to their variable flow rates and nitrogen concentrations. Denitrifying bioreactors that employ a lignocellulosic wood chip medium contained within a saturated (anoxic) zone are relatively new technology that can be implemented at the local level to manage residential non-point nitrogen sources. In these systems, wood chips serve as a microbial biofilm support and provide a constant source of organic substrate required for denitrification. Denitrifying wood chip bioreactors for stormwater management include biofilters and bioretention systems modified to include an internal water storage zone; for on-site wastewater, they include upflow packed bed reactors, permeable reactive barriers, and submerged wetlands. Laboratory studies have shown that these bioreactors can achieve nitrate removal efficiencies as high as 80-100% but could provide more fundamental insight into system design and performance. For example, the type and size of the wood chips, hydraulic loading rate, and dormant period between water applications affects the hydrolysis rate of the lignocellulosic substrate, which in turn affects the amount and bioavailability of dissolved organic carbon for denitrification. Additional field

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studies can provide better understanding of the effect of varying environmental conditions such as ambient temperature, precipitation rates, household water use rates, and idle periods on nitrogen removal performance. Long-term studies are also essential for understanding operations and maintenance requirements and validating mathematical models that integrate the complex physical, chemical, and biological processes occurring in these systems. Better modeling tools could assist in optimizing denitrifying wood chip bioreactors to meet nutrient reduction goals in urban and suburban watersheds.

2.2 Background

Discharge of excess nitrogen to coastal water bodies has led to increasing eutrophication and aquatic dead zones worldwide (LeFevre et al., 2015; UNEP and WHRC, 2007; USEPA, 2005). Managing the nitrogen cycle has been identified as a Grand Challenge by the U.S. National Academy of Engineering (NAE) (NAE, 2008) and imbalances in this cycle are recognized as having harmful effects on human health and the environment (SAB, 2011; UNEP and WHRC, 2007). Significant advances have been made in improving biological nitrogen removal (BNR) processes to manage point sources of nitrogen (Ergas and Aponte-Morales, 2014). However, non-point sources of nitrogen from residential areas, such as stormwater runoff and discharges from on-site wastewater treatment systems, are difficult to control due to their diffuse nature and highly variable flow rates and concentrations. Over the last four decades, these non-point sources have also become a larger percent of the overall nitrogen loading to many coastal waters (Butcher, 2014; LeFevre et al., 2015; Lynn et al., 2016; USEPA, 2005). For example, approximately 10 trillion gallons of untreated stormwater runoff end up in U.S. waterways, which are sources for water supply and recreation (Hobbs and Garrison, 2011), and approximately 60 million people in the U.S. are currently served by on-site septic systems (USEPA, 2016a).
Denitrifying wood chip bioreactors are a viable management tool for control of non-point nitrogen sources in urban and suburban watersheds (Davis et al., 2009; LeFevre et al., 2015; Liu et al., 2014). These bioreactors employ a submerged zone containing wood chips to promote denitrification (Christianson, 2012; Schipper et al., 2010). As shown in Figure 1, the wood chips serve as both a microbial biofilm support and a source of dissolved organic carbon (DOC), which promotes a suitable environment for the growth of heterotrophic denitrifying bacteria (Chu and Wang, 2013). The use of wood chips has been compared with other solid organic substrates for biological denitrification (e.g., maize cobs, wheat straw, green waste, sawdust) and have been found to be the most suitable for maintaining a steady NO$_3^-$ removal, limiting excessive DOC discharges and N$_2$O emissions (Cameron and Schipper, 2010; Healy et al., 2012; Kim et al., 2003; Warneke et al., 2011).

Denitrifying wood chip bioreactors are designed so stormwater or wastewater that enters the bioreactor encounters anoxic conditions that supports denitrification. An advantage of using a solid organic substrate in the bioreactor is that it eliminates the need to provide a liquid feed system for providing chemicals such as methanol, which can be an added expense and is difficult to
handle, deliver, and store (Ergas and Aponte-Morales, 2014). It is also an important and challenging task to supply the proper stoichiometric requirement of chemical inputs under dynamic loading conditions often observed in management of residential stormwater and on-site wastewater. Excessive input of organic substrate can result in carry-over of DOC to the effluent, while too little substrate can result in incomplete denitrification, both negatively affecting the environment (Ergas and Aponte-Morales, 2014). Moreover, lignocellulosic materials are usually available at the local level, minimizing transportation costs. Other societal benefits associated with these nitrogen management technologies include reduced flooding, improved groundwater recharge, the potential for on-site reuse of treated water, incentives and credits to municipalities for increased nitrogen removal, and lower capital and operation and maintenance (O&M) costs (Oakley et al., 2010; Schipper et al., 2010).

Denitrifying bioreactors that employ a lignocellulosic wood chip media are a promising technology for treatment of non-point sources of nitrogen in residential areas. However, identification of key knowledge gaps has not yet been performed that could lead to transformative advances of this technology. Accordingly, the objective of this paper is to provide a critical review of the literature on denitrifying bioreactors employing wood chip media used to manage residential non-point sources of nitrogen, specifically applications for stormwater runoff and on-site wastewater treatment. Prior review articles have focused on the use of denitrifying wood chip bioreactors for treatment of agricultural runoff (Cameron and Schipper, 2010; Ergas et al., 2010; Greenan et al., 2006; Moorman et al., 2010; Robertson, 2010). Those studies informed but were not the focus of this review. Furthermore, although lignocellulosic wood chips are used in a number of other environmental applications, including bioremediation of acid mine drainage (Becerra et al., 2009), biological air pollution control systems (Li et al., 2003; Morgan-Sagastume
et al., 2003), and treatment of aquaculture wastewaters (Saliling et al., 2007), these topics are not discussed here.

2.3 Applications of Denitrifying Wood Chip Bioreactors

As mentioned previously, in many residential areas, the two largest non-point sources of nitrogen are stormwater runoff and on-site wastewater (Carpenter et al., 1998; Poor et al., 2013; USEPA, 2005). Although the application and regulatory requirements for systems treating these sources are different, the denitrifying wood chip bioreactors used for both sources are similar in their design, operation and challenges. For example, both sources have highly variable influent flow rates, pollutant influent concentrations, and chemical forms of nitrogen (which includes ammonium \([\text{NH}_4^+]\), nitrite \([\text{NO}_2^-]\), nitrate \([\text{NO}_3^-]\), dissolved organic N \([\text{DON}]\) and particulate organic N \([\text{PON}]\)). Because of seasonal variations in rainfall or household occupancy, these system experience long dormant periods, which can adversely impact microbial communities carrying out biological processes (Lens et al., 1994; Lynn et al., 2015a). This section thus describes denitrifying wood chip bioreactor configurations for managing these sources of nitrogen.

2.3.1 Biofiltration Systems for Treatment of Stormwater Runoff

Sources of nitrogen in residential stormwater runoff include fertilizer from lawns, atmospheric deposition from stationary and mobile combustion sources, soil, pet waste, and other organic debris (Carey et al., 2013; Davis et al., 2006). Nitrogen concentrations and species in residential runoff vary due to regional and environmental factors such as climate, land use, housing density, and the distribution of air pollution nitrogen sources (Li and Davis, 2014). Typical total nitrogen (TN) concentrations in U.S. stormwater runoff are reported to be 2.0 mg N/L (Schueler, 2003). However, based on land use considerations, TN concentrations can range from 1.0 mg N/L
for landscapes that maintain wetland and forest features to 2.4 mg N/L for landscapes that contain more impervious surfaces (Harper and Baker, 2003). High-density residential areas also experience increases of TN in stormwater runoff to 11.6 mg N/L during the dry season when nutrients have had time to accumulate on impervious surfaces (Francey et al., 2010).

Biofilters, biofiltration systems, and bioretention systems (Figure 2.2) are similar technologies whose names are used interchangeably in the literature. These are considered a low impact development (LID) technology and structural best management practice (BMP) used for stormwater management. Figure 2.3 provides a timeline of the design and research advances for bioretention systems. The first bioretention manual came out in 1993 in Maryland (PGC, 1993) (Figure 2.3).

LIDs attenuate peak flows and improve the quality of stormwater runoff before it enters receiving groundwater and/or surface water. LID technologies are designed to restore or preserve the natural hydrology of a site to before predevelopment conditions by working with the landscape, maintaining natural drainage courses, and reducing imperviousness (PGC, 1999; USEPA, 2016b). Structural LID technologies also include green roofs, permeable pavement, bioswales, and rainwater harvesting. Collins et al. (2010) reviewed TN removal in eight types of stormwater control measures, including conventional and LID technologies (Table 2.1). In their study, they found that modified bioretention systems ranked highest for TN removal at 54.2%, while green roofs and permeable pavement ranked lowest, at 7.4% and -2.4% (TN export), respectively.
Figure 2.2 Six distinct zones in a modified bioretention unit. Top to bottom shows regions of stormwater ponding, mulch, topsoil, nitrification, denitrification (IWSZ) and drainage layers. Wood chips are contained in the denitrification (IWSZ) zone.

Table 2.1 Concentration-based TN removal efficiencies (%) for four low impact development (LID) technologies (adapted from Collins et al., 2010).

<table>
<thead>
<tr>
<th>LID Technologya</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green roofs (n=9)</td>
<td>7.4 %</td>
</tr>
<tr>
<td>Permeable pavement (n=5)</td>
<td>- 2.4 %</td>
</tr>
<tr>
<td>Bioretention - Conventional (n=17)</td>
<td>25 %</td>
</tr>
<tr>
<td>Bioretention - Modified (n=5)</td>
<td>54.2 %</td>
</tr>
</tbody>
</table>

a n is the number of studies

Bioretention systems typically include plants (Figure 2.2), which promote uptake of nutrients, enhance microbial activity in the root zones and contribute DOC for denitrification (Collins et al., 2010; Payne et al., 2014; Read et al., 2008). Bioretention systems are relatively shallow depressions with a planting bed where stormwater runoff slowly infiltrates through different permeable layers such as vegetated soil, sand and gravel (Figure 2.2). Conventional
bioretention systems have been shown to achieve high removal efficiencies for suspended solids, organics, metals, and phosphorus through sedimentation, filtration, adsorption and plant and microbial uptake (Ergas et al., 2010; Li and Davis, 2014). However, a number of studies have shown poor TN removal, with an average of 25% (Table 2.1), and at times the effluent TN concentrations have been reported to exceed the influent concentrations (Collins et al., 2010; LeFevre et al., 2015). This is because conventional bioretention systems typically operate under unsaturated down flow hydraulic conditions, which promotes an aerobic environment. Under these conditions, NH$_4^+$ is oxidized to NO$_2^-$ and NO$_3^-$ via nitrification and exported with the effluent (LeFevre et al., 2015). Dissolved organic nitrogen that leaches from the system may also originate from mulch, compost, soil or decaying plant matter (Hatt et al., 2007; Li and Davis, 2014).

Although, nitrogen removal efficiencies for conventional bioretention systems studied at the laboratory and pilot-scale are reported to range from 50-75% for total Kjeldahl nitrogen (TKN) and 60-80% for NH$_4^+$ (Davis et al., 2006), the export of NO$_2^-$ + NO$_3^-$ (NO$_x$) and DON often negates the more effective removal of PON and NH$_4^+$ (Davis et al., 2006). For example, a net export of 630% of NO$_x$-N (Bratieres et al., 2008) was reported for a conventional bioretention system with organic material placed in the top layers and another laboratory study reported a net export of 204% NO$_3^-$-N (Davis et al., 2001) for a conventional bioretention with plants and shredded hardwood bark as mulch. The National Pollutant Removal Performance Database reports median NO$_x$ and TN removal efficiencies for field studies of conventional bioretention systems of only 43% and 46%, respectively (CWP, 2007).

The highly variable TN removal efficiencies observed in conventional bioretention systems led to the development of modified biofilters or modified bioretention systems in 2003 (Figure 2.3). Kim et al. (2003) first proposed a modification of a conventional biofiltration system to
include an internal water storage zone (IWSZ) containing an electron donor such as wood chips to facilitate denitrification. In these systems, an upturned elbow maintains saturated conditions in the wood chip zone (Figure 2.2), which limits oxygen diffusion to the biofilm, creating the anoxic conditions required for denitrification. Kim et al. (2003) and Hunt (2003) reported that TN removals > 80% could be achieved in laboratory columns with such system. The first field study of a modified bioretention system was in Connecticut and showed TN removal efficiencies of approximately 82% when these systems treated dairy farm runoff.

Figure 2.3 Timeline of design and research advances for bioretention systems.
The long retention time in the IWSZ during antecedent dry conditions (ADCs, number of dry days before a storm event) facilitates dissolution of DOC from the wood chips and denitrification during the dormant period (Lynn et al., 2015a). Laboratory column experiments of an IWSZ filled with eucalyptus wood chips and gravel (1:2 by volume) demonstrated > 80% removal of TN (Lynn et al., 2015a). With the same medium, ~100% removal of NO$_3^-$ was achieved in acclimated anoxic microcosms within 6 hours. The design of a modified bioretention system and selection of the media are thus both important for the efficiency of TN removal.

Reviews of the performance of bioretention systems in the field (Ahiablame et al., 2012; LeFevre et al., 2015) identified 15 conventional and 7 modified bioretention systems (Table 2.2). Field studies have been conducted in only six (primarily eastern) U.S. states (Maryland, Connecticut, North Carolina, Virginia, Florida, and Washington,) and Australia, with modified bioretention system field studies limited to four eastern states. Although research on modified bioretention systems has been on-going since 2003 (Figure 2.3), only two studies have used wood chips at the field scale ((Ergas et al., 2010; Lopez et al., 2016) Table 2.2). Additional field studies are necessary to provide design guidance for implementing modified bioretention systems in different climate zones (e.g., arid, sub-tropical and tropical), with different seasonal sunlight and precipitation patterns, and with different native and common ornamental plants and locally available lignocellulosic materials.
Table 2.2 Residential stormwater field studies focused on removal of dissolved nutrients with a modified bioretention system (adapted from LeFevre et al. (2015)).

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Carbon Source for Modified System</th>
<th>Lined</th>
<th>U.S. Climate Regions defined by NOAA</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maryland</td>
<td>Shredded newspaper</td>
<td>Yes</td>
<td>Northeast</td>
<td>(Hsieh and Davis, 2005)</td>
</tr>
<tr>
<td>2</td>
<td>North Carolina</td>
<td>Not specified. Assuming organic material in fill soil media</td>
<td>Yes</td>
<td>Southeast</td>
<td>(Hunt et al., 2006)</td>
</tr>
<tr>
<td>3</td>
<td>Maryland</td>
<td>Shredded newspaper</td>
<td>Not specified</td>
<td>Northeast</td>
<td>(Davis, 2007)</td>
</tr>
<tr>
<td>4</td>
<td>North Carolina</td>
<td>Not specified. Assuming organic material in fill soil media</td>
<td>No</td>
<td>Southeast</td>
<td>(Passeport et al., 2009)</td>
</tr>
<tr>
<td>5</td>
<td>North Carolina</td>
<td>Assuming organic material in fill soil media</td>
<td>No</td>
<td>Southeast</td>
<td>(Brown and Hunt, 2011)</td>
</tr>
<tr>
<td>6</td>
<td>Connecticut</td>
<td>Wood chips (maple and birch wood)</td>
<td>Yes</td>
<td>Northeast</td>
<td>(Ergas et al., 2010)</td>
</tr>
<tr>
<td>7</td>
<td>Florida</td>
<td>Wood chips (eucalyptus wood)</td>
<td>Yes</td>
<td>Southeast</td>
<td>(Lopez et al., 2016)</td>
</tr>
</tbody>
</table>

2.3.2 Denitrifying Wood Chip Bioreactors for On-Site Wastewater Treatment

On-site wastewater is also referred to as domestic wastewater, residential wastewater, domestic sewage, or a combination of these terms. For simplicity, the term residential wastewater is used here and refers to all the wastewater collected from a residence including water from toilets, showers, kitchen sinks and laundry. Conventional on-site residential wastewater treatment systems consist of a septic tank for solids separation followed by a soil infiltration system (or drain field),
which provides further biological treatment and some pathogen removal. Advantages of on-site wastewater treatment include their simplicity of operation, low installation cost, low O&M requirements and the ability to recharge local groundwater resources (USEPA, 2008). Major challenges of on-site wastewater treatment systems include siting restrictions in areas with a high groundwater table and proximity to drinking water sources and environmentally sensitive areas (FDOH, 2013). As discussed previously, on-site wastewater treatment systems are also subject to highly variable hydraulic and pollutant loading rates and long idle times (e.g., during vacations or seasonal use). In addition, these systems mainly depend on the homeowner to carry out or schedule required maintenance.

Most of the nitrogen in residential wastewater is in the form of PON, DON and NH$_4^+$.

Although nitrification is observed in aerobic regions of the drain field, conditions in conventional on-site wastewater treatment systems do not favor denitrification, resulting in NO$_3^-$ contamination of surface water and groundwater. Mechanical systems that require outside input of electricity that are similar to a centralized activated sludge BNR processes have been developed to improve nitrogen removal in on-site wastewater treatment systems. However, studies of these mechanical systems have shown inconsistent performance, with generally less than 60% TN removal, and problems due to the lack of O&M requirements by homeowners (Costa et al., 2002; Harden et al., 2010; Roeder, 2009).

Because of these challenges, “passive” BNR systems have been developed for on-site wastewater treatment that are similar to conventional septic systems in their O&M requirements (Hirst et al., 2013). Figure 4 shows an example of a passive on-site wastewater BNR system. Nitrification takes place in the first stage, which consists of an unsaturated trickling filter containing sand, expanded clay, gravel or zeolite media (Rodriguez-Gonzalez et al., 2016).
Denitrification takes place in a second stage, which consists of a packed bed reactor containing a “reactive” medium, such as wood chips (Healy et al., 2006) or elemental sulfur pellets (Krayzelova et al., 2014). Recirculation of effluent from the trickling filter back to the septic tank or a separate pre-anoxic tank is often used to dilute the influent to Stage 1 and reduce the influent NO$_3^-$ loading to Stage 2 (Sengupta et al., 2007). Similar to modified bioretention systems that manage stormwater, submerged conditions are normally maintained in the wood chip reactor to favor the development of anoxic conditions while the reactive medium serves as both a microbial biofilm carrier and organic carbon substrate for denitrification (Figure 1). Several of these systems are available commercially, including Nitrex™ (supplied by Lombardo and Associates, Newton, MA) and De-Nyte® (supplied by Presby Environmental, Whitefield, NH) technologies. Other wood chip based denitrification technologies for on-site wastewater treatment include systems that combine nitrification and denitrification stages within a single unit (St. Marseille and Anderson, 2002), permeable reactive barriers (also called denitrification walls (Robertson and Cherry, 1995)) and horizontal or vertical flow wetlands containing wood chips (Fuchs et al., 2012; Saeed and Sun, 2011b).
A timeline showing the development of wood chip bioreactors for on-site wastewater treatment is provided in Figure 2.5. This timeline suggests the field performance of a wood chip bioreactor for on-site wastewater management is more advanced when compared to stormwater management. Lens et al. (1994) carried out studies of treatment of unsettled wastewater in bench scale columns containing peat, bark and wood chip media. Approximately 38% TN removal was observed with wood chips even though the systems were operated as aerobic percolation columns and were not specifically designed for denitrification. Another bench-scale study evaluated pine sawdust, sawdust mixed with soil, and wood chips/sand media for wastewater denitrification in horizontal-flow filters with 26 day empty bed contact times (EBCT = reactor volume/flow rate) (Healy et al., 2006). In that study, the wood chip and sand mixture (1:1 ratio by volume) yielded the best NO\textsubscript{3}\textsuperscript{-} removal performance (> 97%). However, daily addition of sodium sulfite (a dissolved oxygen [DO] scavenger) was required to maintain anoxic conditions in the column.
Nitrified residential wastewater was treated in a packed bed reactor containing a mixture of wood chips and sawdust (Schipper et al., 2010), resulting in consistently low effluent NO$_3^-$ concentrations with little export of organic carbon. Tanner et al. (2012) investigated five different treatment trains for on-site wastewater treatment and concluded that the best overall TN removal (95%) was obtained when a recirculating vertical flow wetland with a sand medium was followed by a packed bed reactor containing wood chips. Rambags et al. (2016) sampled a full-scale wood chip denitrifying bioreactor receiving secondary-treated septic tank effluent. Greater than 99.9% removal of NO$_3^-$ was observed, along with high removal efficiencies for total suspended solids (TSS), fecal indicator bacteria and viruses; however, removal of NH$_4^+$, organic nitrogen, and phosphorus was inconsistent.

Several studies have investigated the use of permeable reactive barriers for on-site wastewater denitrification. In these systems, a permeable wall of wood chips is constructed in the subsurface downstream of the drain field to intercept the NO$_3^-$ contaminated groundwater plume. One study observed almost complete denitrification using this approach (Robertson and Cherry, 1995). Additional studies have been carried out using horizontal flow, vertical flow, and hybrid wetlands systems containing wood chip media that might be useful to guide research for on-site wastewater management. For example, a hybrid wetland system was tested that consisted of a vertical flow wetland with wood chips, followed by a horizontal flow wetland with gravel and finally a vertical flow wetland with zeolite (Saeed and Sun, 2011b). The observed removal of TN (72%) was attributed to both high oxygen transfer for nitrification and organic carbon availability from the wood chips for denitrification. The same authors also compared hybrid systems consisting of vertical flow followed by horizontal flow wetlands with different types of media (gravel, wood chip and a gravel wood chip mixture) (Saeed and Sun, 2011a). Improved TN
removal performance was observed in the systems containing wood chips compared to the traditional system with only gravel, with 98% TN removal in the vertical flow system (Saeed and Sun, 2011a).

Figure 2.5 Timeline of research and design advances for on-site wastewater treatment.

2.4 Process Microbiology

Nitrogen transformation processes that occur in denitrifying wood chip bioreactors include uptake of nitrogen by plants and microorganisms, nitrification, denitrification, dissimilatory reduction of nitrate to ammonia and anaerobic ammonia oxidation (ANAMMOX). Several studies have reported that dissimilatory reduction of nitrate to ammonia plays only a small role in NO$_3^-$ removal in denitrifying wood chip bioreactors (Gibert et al., 2008; Greenan et al., 2006; Warneke
et al., 2011), while little research has been carried out on the role of ANAMMOX in these systems, therefore these processes are not discussed further. Because the electron donor for denitrification is primarily obtained from the wood chips, factors affecting the hydrolysis of lignocellulosic biomass are discussed here.

2.4.1 Nitrogen Transformation Processes

Nitrogen is an important macronutrient that is taken up from the soil and incorporated into plant and microbial biomass. Several studies have compared bioretention systems with and without plants and found that generally, systems with plants perform better at removing nitrogen than systems without plants (Collins et al., 2010; Palmer et al., 2013; Payne et al., 2014; Read et al., 2009). Studies have observed how plant species along with the organic content in the media of the bioreactor and the use of an IWSZ influence the variation of nitrogen removal. In some instances nitrogen leaching has occurred, attributed mainly to leaching of nitrogen from organic matter in the soil (Read et al., 2009). In addition, the presence of plants enhances microbial activity in the root zones, more aerobic conditions for nitrification and contributes DOC for denitrification (Read et al., 2009; Zhai et al., 2013).

Both modified bioretention systems (Figure 2.2) and denitrifying wood chip bioreactors for on-site wastewater treatment (Figure 2.4) are often designed to include an unsaturated zone for nitrification prior to denitrification. Nitrification is an aerobic process, requiring sufficient DO for oxidation of $\text{NH}_4^+$ to $\text{NO}_2^-$ by ammonia oxidizing bacteria and archaea, followed by oxidation of $\text{NO}_2^-$ to $\text{NO}_3^-$ by nitrite oxidizing bacteria. Nitrification performance can be limited by low contact times at high hydraulic loading rates, washout of microorganisms (e.g., due to high shear forces), low temperatures, in low alkalinity waters, insufficient oxygen transfer to the nitrifying biofilm, and due to the presence of toxic organic compounds and metals (Ergas and Aponte-Morales, 2014).
In a laboratory and field study of modified bioretention systems, nitrification appeared to limit TN removal, since TN and NH₄⁺ concentrations were high yet NO₃⁻-N concentrations were below detection limits, indicating complete denitrification (Ergas et al., 2010).

In denitrification, facultative microorganisms respire NO₃⁻ or NO₂⁻ under anoxic conditions (Madigan et al., 1997); therefore saturated conditions that limit oxygen transfer and promote the development of an anoxic zone are normally included in denitrifying wood chip bioreactors. A variety of electron donors can be used for denitrification including inorganic compounds, such as elemental sulfur (Krayzelova et al., 2014) and dissolved organic carbon leached from the wood chips as shown in Figure 2.1 (Fowdar et al., 2015; Lynn et al., 2015a). Denitrification normally proceeds through a series of four sequential steps (NO₃⁻ → NO₂⁻ → NO(g) → N₂O(g) → N₂(g)). A number of genera of denitrifying microorganisms, as well as some archaea and fungi, have been identified including Firmicutes, Actinomycetes, Bacteriodes, Aquifacae, Proteobacteria Alphaproteobacteria, Betaproteobacteria, Gammaproteobacteria and Epsilonproteobacteria (Philippot et al., 2007).

Production of N₂O is a particular concern for BNR processes because it is a potent greenhouse gas and ozone-depleting compound. Studies of denitrifying wood chip bioreactors have shown that N₂O emissions are lower or similar to N₂O emissions from fertilized agricultural fields or systems using other organic carbon sources (Elgood et al., 2010). For example, only a small fraction of the NO₃⁻ removed (0.6%) from a full scale denitrifying wood chip bioreactor in Canada was emitted as N₂O. N₂O emission rates were comparable to those reported for agricultural croplands and less than emissions from nitrogen polluted water bodies (Elgood et al., 2010). In the summer months, the denitrifying bioreactor acted as an N₂O sink (Elgood et al., 2010). Grover et al. (2013) reported that bioretention systems were only minor N₂O sources. Although peak N₂O
emissions from a modified bioretention system were an order of magnitude greater than from a conventional system, concentrations were the same magnitude as fertilized irrigated lawns (Grover et al., 2013). Additional research is needed on characterizing N₂O emissions from denitrifying wood chip bioreactors used to treat on-site wastewater, specifically studies that provide greater insights into the mechanisms of N₂O production under transient loading conditions, and denitrifying wood chip bioreactor designs that minimize N₂O emissions. Although CH₄ emissions for denitrifying wood chip bioreactors are reported as lower than for constructed wetlands, conventional wastewater treatment, and manure composting facilities (Elgood et al., 2010), methane emissions may be a concern because methane is a potent greenhouse gas.

Several studies have investigated the presence of nitrogen transforming genes involved in denitrification in wood chip bioreactors (Chen et al., 2013; Philippot et al., 2007; Zumft, 1997). Chen et al. (2013) quantified nitrifying and denitrifying genes in the sand (nitrifying) and mulch layers of a conventional bioretention system. The results showed that the quantity of nitrifying and denitrifying genes decreased as a function of media depth, possibly due to decreases in DOC availability with depth (Chen et al., 2013). In denitrification beds treating agricultural runoff it was concluded that microbial denitrification was the primary mechanism for NO₃⁻ removal due to the abundance of cytochrome nitrite reductase (nirS) or copper nitrite reductase (nirK) genes (Warneke et al., 2011).

2.4.2 Biodegradation of Lignocellulosic Material

A general stoichiometric equation for denitrification using a simple carbohydrate (CH₂O) as an electron donor can be written as:

\[
5CH_2O + 4NO_3^- + 4H^+ \rightarrow 2N_2 + 5CO_2 + 7H_2O
\]  (2.1)
The simple carbohydrate could be derived from natural organic solid substrates that include wood, compost, leaves, or soil organic matter (Gibert et al., 2008). Wood is primarily composed of lignocellulose that consists of cellulose (45-55% content), hemi-cellulose (24-40%) and lignin (18-35%) (Betts et al., 1991; Pérez et al., 2002). Cellulose is a glucose polymer with α-1,4-linkages, hemicellulose is a heteropolysaccharide polymer and lignin is an amorphous heteropolymer (Malherbe and Cloete, 2002; Pérez et al., 2002). Use of a solid substrate requires the additional step of hydrolysis to first solubilize the organic carbon (Chu and Wang, 2013). Hydrolysis occurs when bacteria excrete extracellular enzymes that break down solid substrates into DOC that has a small enough molecular weight to pass (or dissolve) through the bacteria’s cell membrane (Bruce and Perry, 2001). The rate of hydrolysis of hemicellulose is known to occur fastest, followed by cellulose and then lignin (Malherbe and Cloete, 2002).

The biodegradation of cellulose, hemi-cellulose and lignin requires different enzymes and bacteria (Bruce and Perry, 2001). Cellulose is the most studied compound in mesophilic anaerobic environments, which is an expected operating environment for residential denitrifying bioreactors. Enzymes that depolymerize cellulose in these environments are organized in multi-enzymatic complexes called cellulosomes (Desvaux, 2006). Enzymes found in cellulosomes are known to include endoglucanase, cellobiohydrolase and xylanase (Leschine, 1995). The products of cellulose depolymerization include cellobiose, cellodextrines and glucose, which can be metabolized in biofilms (Desvaux, 2006; Leschine, 1995).

Bacteria and fungi that are known to produce cellulosic hydrolytic extracellular enzymes have also been shown to exhibit other interesting capabilities that may be of importance in wood chip bioreactors (Leschine, 1995). Clostridium cellulovorans is capable of utilizing other carbon sources found in wood, such as xylan (hemicellulose) and pectin (Kosugi et al., 2001); the
cellulosomes of *Clostridium cellulolyticum* are known to facilitate bacterial adhesion onto solid substrates (Desvaux, 2006); in nitrogen-limited environments, *Cellulomonas* spp. can utilize NH$_4^+$ from solid cellulosic substrates for synthesis (Young et al., 2012).

2.4.3 Effect of Transient Loading Conditions on Microbial Processes

Differences have been observed in effluent water quality during start-up, operation, and dormant phases of denitrifying wood chip bioreactors. This may be due to the growth of microbial biofilms on the wood chips as the bioreactors mature with time or changes in the availability of different terminal electron acceptors (Lens et al., 1994). During the start-up phase, denitrifying wood chip bioreactors have been reported in some instances to export high concentrations of DOC and TKN and remove only a small amount of NO$_3^-$ (Lynn et al., 2015a). This may be due to the presence of aerobic conditions initially in the bioreactor. Higher rates of hydrolysis of lignocellulosic material are observed under aerobic compared with anaerobic conditions (Leschine, 1995; Malherbe and Cloete, 2002; Tomme et al., 1995), resulting in more leaching of DOC and DON from the system (Lynn et al., 2015a; Sulaiman and Lee, 2012). In addition, performance is expected to improve as denitrifying biofilms are established in the reactors. The duration of the start-up phase for denitrification has been shown to be between six hours and one month (Lynn et al., 2015a); however, the precise time-scale for start-up is unknown. Extended start-up periods are reported to be required for bioretention systems (Ergas et al., 2010) and wastewater treatment systems (Lens et al., 1994) that included unsaturated zones for nitrification. Nitrifiers are slow growing autotrophs that require longer acclimation periods (Ergas and Aponte-Morales, 2014).

NO$_3^-$ removal rates increase as anoxic conditions are established, which facilitate the activity of denitrifying organisms (Peterson et al., 2015). In systems where both DO and NO$_3^-$ are
present in the influent (Lynn et al., 2015a; Smith, 2008) and a carbon source is available in excess, microbial communities will first utilize DO as an electron acceptor. DO is more energetically favorable. Once DO is depleted below a certain level, the microorganisms will switch to utilizing NO$_3^-$ (Madigan et al., 1997). Lynn et al. (2015a) estimated an oxygen inhibition coefficient value for the Andrew’s equation of 2.2 mg/L in a wood chip stormwater biofilter microcosm study.

During operation, excess DOC washes out of the bioreactor pore water as the influent water “mixes” with the water retained in the bioreactor pore water (Lynn et al., 2015a). This decrease in pore water results in decreased NO$_3^-$ removal at high flow rates or longer periods of continuous operation (Lynn et al., 2015a). At lower hydraulic loading rates, NO$_3^-$ removal rates increase as denitrifiers have more contact time to utilize NO$_3^-$ in the water.

During the dormant phase when the reactor is not receiving influent, NO$_3^-$ will become depleted, DOC concentrations will increase, oxidation reduction potential will decrease, and sulfate reduction can occur (Elgood et al., 2010; Lynn et al., 2015a; Robertson, 2010), resulting in odorous hydrogen sulfide production. Decreases in pore water DOC concentrations were observed after an extended dormant period (e.g., > 16 days) (Lynn et al., 2015a) possibly due to the growth of methanogens (Elgood et al., 2010).

### 2.5 Physical Characteristics and Operating Conditions that Impact Design & Performance

A number of factors influence the performance of denitrifying wood chip bioreactors including: (1) physical characteristics such as wood chip type and size and bioreactor depth; and (2) operating conditions such as hydraulic loading rate, hydraulic retention time, length of antecedent dry conditions, influent nitrogen concentration, temperature, other additives present in the media, media saturation and media longevity (Cameron and Schipper, 2010; Lynn et al., 2015a; Schipper et al., 2010; Subramaniam et al., 2015).
2.5.1 Wood Chip Type and Size

The wood chip medium used in denitrifying wood chip bioreactors has been obtained from hardwood and softwood trees (Table 2.3). Hardwood trees have broader leaves and a higher carbon content and density than softwoods (Ma, 2015). In general, observed TN removal rates are higher with softwood compared with hardwoods (Table 2.3). However, Peterson et al. (Peterson et al., 2015) observed higher TN removals with the hardwoods Willow Oak and Red Maple than Virginia Pine softwood. These studies suggest that future research could determine the exact mechanism(s) that cause a particular wood chip type to influence the denitrification rate or long-term NO$_3^-$ removal performance. In addition, life cycle and economic assessments can assist our understanding of the environmental sustainability and cost of different materials.

Two studies evaluated the effect of wood chip size on the performance of denitrifying bioreactors (Cameron and Schipper, 2010; Peterson et al., 2015). Cameron and Schipper (2010) reported a slight increase in NO$_3^-$ removal rate with increasing wood chip size but the difference was statistically insignificant. Larger sized wood chips may contribute to higher porosity in the bioreactor greater internal pore structure that may lead to greater water holding capacity of a reactor. In contrast, Peterson et al. (2015) found that NO$_3^-$ removal efficiencies were higher with smaller wood chip sizes. Smaller wood chips have a higher total surface area per unit mass, leading to more area for biofilms to grow (Figure 1). However, smaller wood chips would be expected to also leach more TKN, which can offset some of the improvements in overall nitrogen removal (Peterson et al., 2015). The results from these studies demonstrate how wood chip size influences a number of other factors (e.g., porosity of the IWSZ, DOC leaching rates) that can play a role in increasing or reducing NO$_3^-$ removal rates. In addition, the contradicting results for nitrogen removal with wood chip size may be due to the higher influent NO$_3^-$ concentration used in the
wastewater (Cameron and Schipper, 2010) compared to the stormwater study (Peterson et al., 2015).

Table 2.3 Collected Data for Nine Different Types of Wood Chips. Type of Study Performed, Carbon Content, TOC Leaching, Influent and Effluent Nitrogen Concentrations, and Nitrogen Removal.

<table>
<thead>
<tr>
<th>Wood Type</th>
<th>Type of Study</th>
<th>Carbon Content (%)</th>
<th>Leached TOC (mg TOC/L)</th>
<th>Influent Concentration (mg N/L)</th>
<th>Effluent Concentration (mg N/L)</th>
<th>N – Removal (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>Column</td>
<td>47</td>
<td>100</td>
<td>3</td>
<td>1.56</td>
<td>48</td>
<td>(Peterson et al., 2015)¹</td>
</tr>
<tr>
<td>Pine</td>
<td>Column</td>
<td>-</td>
<td>-</td>
<td>15.8</td>
<td>11.1</td>
<td>30</td>
<td>(Warneke et al., 2011)</td>
</tr>
<tr>
<td>Pine</td>
<td>Column</td>
<td>28</td>
<td>158</td>
<td>50</td>
<td>&lt; 2.0</td>
<td>96</td>
<td>(Gibert et al., 2008)</td>
</tr>
<tr>
<td>Pine</td>
<td>Column</td>
<td>28</td>
<td>175.3</td>
<td>50</td>
<td>17.7</td>
<td>65</td>
<td>(Gibert et al., 2008)</td>
</tr>
<tr>
<td>Pine</td>
<td>Column</td>
<td>50</td>
<td>-</td>
<td>26</td>
<td>1.8</td>
<td>93</td>
<td>(Healy et al., 2012)</td>
</tr>
<tr>
<td>Pine</td>
<td>Batch</td>
<td>47</td>
<td>-</td>
<td>57.8</td>
<td>6.4</td>
<td>89</td>
<td>(Fowdar et al., 2015)</td>
</tr>
<tr>
<td>Coniferous</td>
<td>Batch</td>
<td>44</td>
<td>-</td>
<td>32.2</td>
<td>1.6</td>
<td>95</td>
<td>(Gibert et al., 2008)</td>
</tr>
<tr>
<td>Willow</td>
<td>Batch</td>
<td>47</td>
<td>120</td>
<td>32.2</td>
<td>4.5</td>
<td>86</td>
<td>(Gibert et al., 2008)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>41.5 (9.3)</strong></td>
<td><strong>138.3 (34.4)</strong></td>
<td><strong>33.4 (18.7)</strong></td>
<td><strong>5.84 (5.8)</strong></td>
<td><strong>75.2 (24.9)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>Column</td>
<td>51</td>
<td>-</td>
<td>2.3</td>
<td>BDL</td>
<td>100</td>
<td>(Lynn et al., 2015a; Lynn et al., 2015b)⁠¹</td>
</tr>
<tr>
<td>Eucalyptus</td>
<td>Column</td>
<td>-</td>
<td>-</td>
<td>15.8</td>
<td>9.9</td>
<td>37</td>
<td>(Warneke et al., 2011)</td>
</tr>
<tr>
<td>Maple</td>
<td>Column</td>
<td>49</td>
<td>42</td>
<td>3</td>
<td>1.1</td>
<td>62</td>
<td>(Peterson et al., 2015)</td>
</tr>
<tr>
<td>Maple/Birch</td>
<td>Pilot</td>
<td>-</td>
<td>-</td>
<td>7.6</td>
<td>0.9</td>
<td>88</td>
<td>(Ergas et al., 2010)</td>
</tr>
<tr>
<td>Red Gum</td>
<td>Batch</td>
<td>44</td>
<td>-</td>
<td>55</td>
<td>7</td>
<td>87</td>
<td>(Fowdar et al., 2015)</td>
</tr>
<tr>
<td>Wild Cherry</td>
<td>Column</td>
<td>50</td>
<td>153</td>
<td>3</td>
<td>1.9</td>
<td>36</td>
<td>(Peterson et al., 2015)</td>
</tr>
<tr>
<td>Oak</td>
<td>Column</td>
<td>50</td>
<td>41</td>
<td>3</td>
<td>1.2</td>
<td>62</td>
<td>(Peterson et al., 2015)</td>
</tr>
<tr>
<td>Beech</td>
<td>Column</td>
<td>50</td>
<td>45</td>
<td>3</td>
<td>2</td>
<td>32</td>
<td>(Peterson et al., 2015)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>48.8 (2.5)</strong></td>
<td><strong>70.3 (55.2)</strong></td>
<td><strong>11.6 (18.1)</strong></td>
<td><strong>3.45 (3.6)</strong></td>
<td><strong>63.0 (26.6)</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Standard deviation (if applicable) in parenthesis. BDL: below detection limit

¹ Study that reported ADC
2.5.2 Saturated Zone Depth

The depth of the saturated zone can influence the performance of denitrifying biofilters for both stormwater and on-site wastewater treatment. Lynn et al. (2016) studied denitrifying wood chip biofilter with varying depths that were operated with the same HRT. Greater NO$_3^-$ removal was reported in taller columns (45 and 60 cm) compared to a shorter column (30 cm) at HRTs $\geq 3$ hours. Tracer studies revealed that dispersion dominated transport was more pronounced in the shorter column. Similarly, a minimum IWSZ depth of 45 cm was reported by Zinger et al. (2007) as optimal for TN removal. This same depth is included in the design depth recommendations by the Facility for Advancing Water Biofiltration (FAWB, 2009). This could potentially limit subsurface applications of denitrifying wood chip bioreactors in regions with high water tables or require larger overall volumes for shallower reactors. Thus, greater understanding is needed of the interplay between IWSZ depth, denitrification performance, and associated costs.

2.5.3 Hydraulic Loading Rate

In a similar way that an increase in column depth improves NO$_3^-$ removal due to longer HRT, a decrease in hydraulic loading rate can also increase retention time and improve NO$_3^-$ removal. Hydraulic loading rates for stormwater and on-site wastewater are naturally variable, but they can be reduced when incorporating a flow control devices at the bioreactor outlet (LeFevre et al., 2015; Lucas and Greenway, 2011; Lucas and Sample, 2015). Lucas and Greenway (2011) installed a regulated outlet in bioretention mesocosms, which increased the HRT from 15 minutes as free flow discharge to about 150 minutes when regulated. The authors observed up to 2.7 times greater NO$_x$ removal with increased retention time. Similarly, for denitrifying bioreactors in the field, a regulated outlet control device could provide additional retention time for denitrification but additional ponding area storage capacity may be required if the influent flow rate is greater
than the regulated effluent flow rate. For on-site wastewater, flow equalization or a decrease in water use within the household through more water efficient technologies or behavioral change could improve NO$_3^-$ removal.

2.5.4 Intermittent Conditions

Intermittent loading conditions in denitrifying wood chip bioreactors are due to variations in nitrogen concentrations and diurnal fluctuations in residential water use and/or varying precipitation patterns associated with stormwater runoff. Intermittent operation constantly changes the biochemical processes that influence nitrogen transformation and DOC dissolution (Section 2.4.3). The impact of intermittent operational conditions in these systems in not well studied and should consider differences in physical, chemical and microbial processes that influence nitrogen removal performance during start-up, operation, and dormant phases.

2.5.5 Longevity

For practical application, the longevity of municipal denitrifying bioreactors is expected to be decades. Field studies performed on on-site wastewater treatment systems have reported appreciable denitrification activity after 15 years of operation (Robertson, 2010; Robertson et al., 2008) and a microcosm study performed on stormwater denitrifying bioreactors estimated wood chip longevity of 21 years (Lynn et al., 2016). These findings fall within the estimated range of 9 to 72 years proposed for agricultural denitrifying bioreactors (Christianson, 2012). However, bioreactor saturation conditions may significantly affect bioreactor longevity. For example, a field study on agricultural denitrifying bioreactors observed increased wood chip degradation in an unsaturated-prone zone of a denitrification wall compared to a saturated-prone zone (Moorman et
al., 2010). These results indicate that saturated conditions should be maintained to sustain the longevity of denitrifying wood chip bioreactors.

2.6 Modeling of Denitrifying Wood Chip Bioreactors

Although several studies highlight TN removal in denitrifying wood chip bioreactors used for stormwater runoff or on-site wastewater, few studies have developed quantitative models to assess the overall TN reduction effectiveness or guide future research. Without these models, TN load reduction design standards may be unreliable, and the flexibility of the designer may be limited to dimensionally “fit” these systems into unique site characteristics. For example, during large storm events, much of the untreated stormwater runoff may by-pass the denitrifying bioreactor by overflowing from the ponding area. This large volume of untreated runoff may result in low overall TN reductions for the system regardless of TN removal efficiency of the bioreactor. Likewise, for on-site wastewater treatment systems, if not sized properly for the incoming flow and volumes, the intended efficiency of nitrogen removal may not occur. When developed, these models could be applied to other wood chip denitrifying bioreactors such as permeable reactive barriers or biofilters used to remove NO$_3^-$ from agricultural runoff. Two challenges in developing these models is the accurate modeling of complex nitrogen transformation processes that occur at the biofilm-scale and integrating these models into watershed-scale hydrological modeling programs for groundwater transport (on-site wastewater) or surface water transport (stormwater).

Current models for stormwater management, such as the U.S. Environmental Protection Agency (USEPA) Stormwater Management Model (SWMM), RECARGA, and DRAINMOD, focus more on the hydraulics and hydrology of the system rather than water quality. Two studies have however developed models that address water quality for denitrifying stormwater bioreactors. Deng et al. (Deng et al., 2012) developed a model for bioreactors containing different organic
carbon amendments and included processes for dispersion, mass transfer of NO$_3^-$ into the biofilm, microbial growth, oxygen inhibition, DOC substrate limitation and temperature. This model may be useful for investigating NO$_3^-$ rate limiting factors that occur within microbial biofilms. A denitrification model that is compatible with SWMM version 5.1 has also been developed that can be used when designing stormwater management systems for land development projects (Lynn, 2017). The processes included in that model are wood chip dissolution and a denitrification kinetic model that incorporates DO and bioavailable DOC. This model may be useful for simultaneously evaluating water quality (e.g., NO$_3^-$ removal) and water quantity (e.g., runoff volume/rate reduction) goals based on a stormwater system design. Although the model predicted NO$_3^-$ removal within 10% of experimental results and is validated with a high Nash-Sutcliffe efficiency coefficient of 0.8, it was recommended that the model be validated and calibrated with field data. These two denitrification models (Deng et al., 2012; Lynn T.J., 2017) could also be improved by integrating a nitrification component to quantify TN load reduction effectiveness according to the specified use (e.g., on-site or stormwater) and bioreactor geometries. Advancement of knowledge on biological process within the different layers of denitrifying wood chip bioreactors can also improve modeling efforts to assist in watershed scale studies and the impact of implementing these systems at hotspots for nitrogen or sensitive ecosystems (Liu et al., 2014).

2.7. Conclusions

Denitrifying wood chip bioreactors can assist in removing nitrogen from non-point sources of residential pollution, such as stormwater runoff and on-site wastewater. The wood chip medium (a lignocellulosic substrate) provides a support structure for biofilms and the organic carbon source required for heterotrophic denitrifying bacteria that is essential for the transformation of reactive nitrogen to unreactive dinitrogen gas. Advantages of these passive systems are that they can handle
the highly variable flow rates and nitrogen concentrations observed in stormwater runoff and on-site wastewater treatment. The use of a solid organic substrate obviates the need for liquid chemical feed systems and reduces the risk of carry-over of excess organic carbon into the effluent. Denitrifying wood chip bioreactors are considered appropriate technologies because they have minimal mechanical energy and chemical inputs and use plant-based and locally available materials such as wood chips, sand, and gravel. In addition, they provide benefits of groundwater recharge and opportunities for water reuse close to the site of wastewater generation in addition to nutrient removal.

Biofilters and bioretention systems that include an IWSZ containing wood chips achieve improved nitrogen removal from stormwater runoff than conventional BMPs. The performance of these systems depends largely on hydraulic and pollutant loading, which fluctuate with individual storm events and seasonal use and precipitation and thus is dependent on geographic location. However, little research has examined the performance of these systems under dynamic loading conditions in different climates, such as arid or tropical climates. With increasing changes in climate and more extreme weather events influencing precipitation and antecedent dry conditions, additional field studies that are linked to modeling will help understand the long-term performance and potential benefits of these systems (Coumou and Rahmstorf, 2012).

A number of different denitrifying wood chip bioreactor process configurations have been successfully used to remove nitrogen from on-site wastewater, including packed bed reactors, permeable reactive barriers and submerged wetlands, with and without recirculation. Although, additional research on the dynamic performance of these systems would provide consistent and long-term nitrogen removal efficiency. Also, use of life cycle assessment and life cost analysis could assist efforts to quantify the economic and environmental tradeoffs between on-site nutrient
removal versus expansion of sewers and centralized wastewater treatment systems for rural and suburban areas.

The type and size of the wood chips, hydraulic loading rate, and dormant period between periods of water application (e.g., during storm events or residential water use) have been shown to affect the hydrolysis rate of the lignocellulosic substrate, which affects the amount and bioavailability of DOC for denitrification. In addition, maintaining saturated conditions during non-operational periods is a critical design feature that controls the overall performance of denitrifying bioreactors. Higher NO$_3^-$ removal, lower TKN export and longer wood chip media longevity is expected from these designs compared with bioreactors that are only designed for saturation during operation. Future research could focus on understanding the interrelationships between bioreactor parameters and developing mathematical models and design tools that can be used to quantify water quality and quantity performance as a function of varying bioreactor designs and environmental conditions. In addition, most studies of wood chip bioreactors have been performed on the individual performance of bench- or field-scale units rather than evaluating the impact of multiple systems on ground and surface water quantity and quality within a watershed. Lastly, life cycle assessments and life cost analysis studies are areas of research that can provide a holistic overview of the sustainability of implementing these systems at the watershed scale.
Chapter 3: Long-Term Field Performance of a Conventional and Modified Bioretention System for Removing Dissolved Nitrogen Species in Stormwater Runoff

3.1 Abstract

Bioretention systems are efficient at removing particulates, metals, and hydrocarbons from stormwater runoff. However, managing dissolved nitrogen (N) species (dissolved organic N, NH$_4^+$, NO$_2^-$, NO$_3^-$) is a challenge for these systems. This paper reports the results of a long-term field study comparing N removal of: 1) a modified bioretention system that included an internal water storage zone containing wood chips to promote denitrification and 2) a conventional bioretention system. The systems were studied, without and with plants, under varying hydraulic loading rates (HLRs) and antecedent dry conditions (ADCs). Both bioretention designs were efficient at removing NH$_4^+$ (83% modified, 74% conventional), while removal of NOx (NO$_2^-$-N + NO$_3^-$-N) was significantly higher in the modified system (81% modified, 29% conventional). Results show that the addition of an internal water storage zone promotes denitrification, resulting in lower effluent TN concentrations (< 0.75 mg/L modified, ~1.60 mg/L conventional). The lowest HLR studied, 4.1 cm/hr, provided the longest hydraulic retention time in the internal water storage zone (~3 hours) and had the greatest TN removal efficiency (90% modified, 59% conventional). In contrast to prior short-term studies, ADCs between 0 to 13 days did not significantly affect DOC export or TN removal. A short-term study with Florida friendly vegetation indicated that TN

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removal performance was enhanced in the conventional bioretention system. This field study provides promising results for improving dissolved N removal by modifying bioretention systems to include an internal water storage zone containing wood chips.

3.2 Introduction

It is estimated that by 2050 20% of the earth’s population will face impaired water quality from excessive nutrients (e.g., nitrogen (N) and phosphorus (P)) including algal blooms, eutrophication, dead zones and drinking water contamination (Paerl and Paul, 2012; Veolia and IFPRI, 2015). In the United States (U.S.) stormwater runoff is the largest diffused source of anthropogenic urban pollution of dissolved N and P (Dressing et al., 2016; Veolia and IFPRI, 2015). Accordingly, with an increase in urbanization, there is a need to integrate low impact development technologies into the urban landscape that not only mitigate wet weather flooding events, but also manage nutrient pollution (Luell et al., 2011). The use of low impact development, or what is most commonly referred to as green stormwater infrastructure, is a promising way to manage stormwater. Low impact development aims to restore the natural hydrology of a site to predevelopment conditions by mimicking natural process, such as infiltration and evapotranspiration, manage stormwater close to the source, and improve water quality (Ahammed, 2017).

Bioretention systems are also commonly referred to as biofiltration systems, rain gardens, or bioswales for their similarities in appearance and construction. Conventional bioretention systems consist of a depression in the land underlain with mulch, and well-drained media, such as vegetated soil, sand, and/or gravel layers (Ahiablame et al., 2012). They can be constructed from locally available materials, have the ability to reduce stormwater runoff volume by storing and infiltrating runoff, have a smaller footprint than other stormwater control measures, such as wet
or dry ponds, increase the biodiversity of a site and are aesthetically pleasing (Ahammed, 2017).

In addition, bioretention systems are efficient at removing many pollutants of concern; for example, suspended solids, hydrocarbons, fecal indicator bacteria (Davis et al., 2009), P (Bratieres et al., 2008; Li and Davis, 2016), and heavy metals (Hatt et al., 2009). However, NOx ($\text{NO}_3^- + \text{NO}_2^-$) is reported to leach from conventional bioretention systems resulting in poor total nitrogen (TN) removal. A wide range of TN removal efficiencies have been reported, between -630% to 46% (Bratieres et al., 2008; Collins et al., 2010; Jiang et al., 2015; LeFevre et al., 2015). In these systems, the porous topsoil and sandy layer promotes adsorption of ammonium ($\text{NH}_4^+$), ammonification and nitrification due to aerobic conditions (Collins et al., 2010). However, removal of $\text{NO}_3^-$ requires denitrifying conditions, with both anoxic conditions and the presence of an electron donor.

One way to improve management of dissolved N species is by modifying the drainage configuration of a bioretention system to incorporate an internal water storage zone (IWSZ) (i.e., a submerged zone or saturated zone) that includes a solid organic carbon source as an electron donor (e.g., wood chips) to promote denitrification. This configuration will be referred to as a modified bioretention system hereinafter in this paper (Lopez-Ponnada et al., 2017). The fully submerged bottom layer promotes the development of anoxic conditions favorable for denitrifying bacteria that use $\text{NO}_3^-$ as their terminal electron acceptor for respiration. For example, Wang et al. (2018) performed a laboratory study on a bioretention system with a relatively high influent $\text{NO}_3^-$ concentration compared with typical urban runoff. The authors reported that the inclusion of an IWSZ increased removal efficiencies for $\text{NO}_3^-$ (-23% to 62%) and TN (35% to 73%) when compared to a conventional system that did not contain an IWSZ. Furthermore, other laboratory
studies reported an increase in NO$_3^-$ and TN removal performance when wood chips are incorporated into the IWSZ layer (Kim et al., 2003; Lynn et al., 2015a; Peterson et al., 2015).

Types of electron donors used in media for denitrifying bioreactors include hardwood and softwood chips, sawdust, maize cobs, green waste, wheat straw, compost, newspapers, and elemental sulfur (Lopez-Ponnada et al., 2017). Lynn et al. (2015a) evaluated the use of eucalyptus wood chips (a hardwood) mixed with various media for the IWSZ. Their results indicated that a mixture of gravel and wood chips (2:1, vol/vol) resulted in greater NO$_3^-$ removal and lower export of dissolved organic carbon (DOC) when compared to using only sand or wood chips.

Several urban and agricultural studies have investigated the field performance of modified bioretention systems (Ergas et al., 2010; Hsieh and Davis, 2005; Luell et al., 2011). Ergas et al. (2010) studied a modified bioretention system with hardwood chips treating dairy farm runoff in temperate northeastern U.S. Influent concentrations were high relative to urban stormwater runoff, yet the system achieved greater than 88% TN mass removal efficiency, with effluent TN concentrations below 10 mg/L. Other field studies of modified bioretention system have included employing an IWSZ without a solid carbon source (Brown and Hunt, 2011; Davis, 2007; Hsieh and Davis, 2005; Hunt et al., 2006; Willard et al., 2017). In some instances, NOx leaching was observed (Brown and Hunt, 2011; Hunt et al., 2006; Liu et al., 2014; Passeport et al., 2009; Willard et al., 2017). However, an evaluation of the performance of a field scale stormwater bioretention system that incorporates a permanently saturated IWSZ containing wood chips has not yet been reported.

In addition, while the presence of plants in a bioretention system is encouraged to provide an aesthetic element and increase biodiversity they may also improve water quality. This is because plants have been shown to assist in nutrient uptake, enrich the microbial community in the
rhizosphere, improve infiltration and hydraulic conductivity, and prevent clogging (Muerdter et al., 2018). Read et al. (2008) suggested that to improve N removal, denitrification is a more permanent N removal pathway than uptake of N by plants. However, Lucas and Greenway (2011) demonstrated that N removal by plant uptake was the most apparent and quantifiable process, with annual N uptake ranging from 51 to 65 g/m²-yr. The latter value was observed for mature systems with plants. Other bioretention studies have reported higher TN removal when plants were present, although most of these studies were conventional systems and only a few studies have been carried out with modified systems (Barrett et al., 2013; Goh et al., 2017; Henderson et al., 2007; Lucas and Greenway, 2011). Payne et al. (2014) reported that TN removal improved in planted modified bioretention columns compared with conventional systems or unplanted columns. Twenty native Australian plant species were used, and the researchers found that plants were not critical for TN removal during the wet period. During the dry period, however, the presence of an IWSZ assisted in maintaining higher soil moisture to support plant survivability. As a result, plant nutrient uptake and microbial processes were enhanced between storm events.

The number of dry days in between storm events (referred to as antecedent dry conditions (ADC)) has also been shown to impact TN removal in bioretention systems (Lynn et al., 2015b). Longer ADCs contribute to wood chip dissolution, increasing the DOC concentration in the IWSZ pore water, and increasing the rate of heterotrophic denitrification. Improved NO₃⁻ removal has been observed in the modified systems with long ADCs compared to periods with frequent storm events (i.e. shorter ADCs) (Lynn et al., 2015b). However, little is known about the influence of ADC on conventional and modified bioretention systems under field conditions.

In this study we investigated the N removal performance of side-by-side, field-scale conventional and modified bioretention systems. The systems were acclimated for two years prior
to start of our field experiments, after which N removal performance was investigated in unplanted (year 3) and planted (year 4) systems. The overall goal of this study was to evaluate the N removal performance in the field of a conventional and modified bioretention system under different conditions. The study specifically investigated the role of: 1) varying hydraulic loading rates, 2) varying ADCs, and 3) presence of plants, on N mass removal efficiency in a conventional and modified bioretention system. A detailed analysis of the fate of dissolved nitrogen species (organic N, NH$_{4}^{+}$, NOx, and TN) and dissolved organic carbon (DOC) during the storm events allowed us to investigate the transient performance of these systems. To the best of our knowledge, this is the first long-term field comparison of a stormwater bioretention system incorporating a permanently saturated IWSZ layer containing wood chips and a conventional system. Many innovative technologies developed in the laboratory are known to not be implemented full-scale because adoption of a new technology depends on time and resource intensive cycles of testing and validation (Mihelcic et al., 2017). It is hoped the promising results of this study will lead to more widespread adoption of bioretention systems for nitrogen management of stormwater.

### 3.3 Materials and Methods

3.3.1 Field Site

One conventional and one modified field-scale bioretention system were operated side-by-side in East Tampa, FL. Stormwater from East Tampa drains to McKay Bay, an embayment of Tampa Bay and a U.S. estuary of national concern where N is a limiting nutrient. A map of the site is provided in Chapter 5. Media profiles and specifications for both systems are provided in Figure 3.1 and Table 3.1. The modified bioretention system was 122 cm (length), 45.7 cm (width), and 97 cm (height) and was composed of the following media materials from top to bottom: a) ~2
cm of pea gravel as a mulch layer, b) 30-cm sand layer, c) 30-cm IWSZ layer consisting of one part eucalyptus wood chips and two parts brown river rock (by volume), resulting in a porosity of 0.42 (Lynn et al., 2015b), d) 5-cm brown river rock, and e) a 30-cm limestone under-drain layer. The conventional system was the same except it did not contain the 30-cm IWSZ layer and was only 67 cm in height. An image of the eucalyptus wood chips used in the modified system is provided in Figure 3.2.

In between the sand and pea gravel layers, a drainage filter fabric (Soil Separator Model # 36150SSF-6) was installed to prevent movement of the sand into the under-drain layer. The filter fabric was added after we observed sand in the underdrain and effluent samples; however, the filter fabric could potentially be a site for excess biofilm growth and lead to clogging. Both systems were encased underground in a wooden frame made of 5-cm x 10-cm wood beams with an impermeable 45-Mil geomembrane liner. The liner aided in effluent sample collection from both systems and also aided in retaining water in the 71-L IWSZ. On the surface, flexible garden lawn plastic edging (Vigoro Model # 8748V) was used on the perimeter of each bioretention cell to delineate them, keep the mulch pea gravel in place, prevent influent stormwater from running off to the sides, and allow for ponding of water during high hydraulic loading rate (HLR) events. The under-drain layer of both systems included a 10-cm diameter perforated PVC pipe to discharge effluent by gravity to an unlined underground trench and ultimately to groundwater. For the modified system, the under-drain pipe had an upturned elbow raised to the top of the IWSZ layer to maintain saturated anoxic conditions required for denitrification (Kim et al., 2003). The systems were originally installed in November of 2013 and acclimated in the field for two years before running the experimental storm events described here.
Figure 3.1 Cross-section schematics of (A) modified bioretention cell and (B) conventional bioretention cell. For both cells, effluent drains through the underdrain pipes and into the underground trench.

Table 3.1 Locally sourced media used in profiles of bioretention systems.

<table>
<thead>
<tr>
<th>Media</th>
<th>Size</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 Paver Sand</td>
<td>0.074 - 2.36 mm</td>
<td>Total Landscape Supply, Sarasota County, FL</td>
</tr>
<tr>
<td>Pea Gravel Mulch</td>
<td>0.6 - 1.3 cm</td>
<td>Home Depot</td>
</tr>
<tr>
<td>Brown River Rock</td>
<td>1.3 cm</td>
<td>Total Landscape Supply, Sarasota County, FL</td>
</tr>
<tr>
<td>#57 Limestone</td>
<td>0.6-2.5 cm</td>
<td>Total Landscape Supply, Sarasota County, FL</td>
</tr>
<tr>
<td>Eucalyptus Wood Chips</td>
<td>1.3-2.5 cm</td>
<td>Sarasota County Government, Sarasota County FL</td>
</tr>
</tbody>
</table>
3.3.2 Synthetic Stormwater Composition

Synthetic stormwater with N levels reported in other studies of urban runoff, was used as the influent during controlled storm events (Harper and Baker, 2007; Yang and Toor, 2017). The synthetic stormwater consisted of tap water with added potassium nitrate, ammonium chloride, and ground live oak (*Quercus virginiana*) tree leaf extract (described below) to achieve 1 mg/L of NH$_4^+$-N, 1 mg/L of NO$_3^-$-N, and ~1 mg/L of dissolved organic N (DON). The tap water was stored in 210-L rain barrel drums at the field site for ≥ 24 hours prior to each storm event to allow the chlorine to dissipate.

Extract from ground live oak leaves was used to represent the dissolved organic nitrogen compounds that would normally be present in urban runoff as a result of dissolution of leaf litter and other organic materials. The dried leaves were ground using a coffee grinder (Mr. Coffee™ Model # IDS55-RB) for approximately one minute. Nine grams of ground tree leaves were then added to a nylon mesh bag (7.6 cm x 10.2 cm) (Dollar Tree SKU: 975579) and sealed with drawstrings to form a tea bag. The tea bag was placed into a 1-L bottle with 800 mL of DI water,
mixed and left to steep overnight. The extract was then added to the synthetic stormwater at a rate of 3.8 mL/L to achieve the target dissolved Org-N concentration of 1 mg/L.

3.3.3 Experimental Field Program

The bioretention systems were operated in two phases (Table 3.2); without plants (referred to as Phase I) and with plants (referred to as Phase II); and at varying HLR, storm duration and ADCs. Storm events in Phase I were conducted in triplicate while storm events in Phase II were conducted in duplicate. Phase I ran from January to July 2016 using HLRs (cm/h) of 4.1, 6.9, and 13.9, with respective hydraulic retention times (HRT) for the IWSZ of 3.1, 1.9, and 0.9 hours, respectively. These HRTs were calculated based on an IWSZ porosity of 0.42. HLRs were selected to compare with results from two previous bench-scale studies (Davis et al., 2006; Lynn et al., 2015b). The HLRs were maintained using a peristaltic pump (Cole-Palmer Masterflex L/S, Model # 07528-10 with Easy-load II pump drives, Model # 77200-50) that applied synthetic stormwater from the rain barrels to the surface of the bioretention systems. The influent was applied through perforated tubing that ran across the middle of each cell on the longest side to provide an even distribution of the water on the surface of both systems.

The systems were exposed to actual stormwater runoff from the site, mainly runoff from a building roof, and environmental conditions for two full years prior to the start of the field experiments. Field conditions are important in analyzing the performance of these systems since with the change in seasons and time they change the materials and microbiome, the diverse microbial community, of the system compared to laboratory scaled systems (Ashoori et al., 2019; Pinto et al., 2014). For the purpose of this study and based on observations, if the amount of natural rainfall during a day was less than 1.9 cm it was counted as a dry day for calculation of ADC. This is the amount of precipitation that if falling directly over the modified bioretention cell would
replace 15% of the volume within the IWSZ. A USGS rain gauge (275917082222500) near the field site provided precipitation data.

In Phase II (March to August 2017), each bioretention system was planted with five plants, after which each Phase I HLR storm event was repeated in duplicate to test the effect of plants on N removal performance for both systems (tests referred to as SE1-P – SE6-P in Table 2). Native Florida friendly plants were utilized. Four dwarf pentas (*Pentas lanceolate*), two 1-quart size pots and two 1-pint size pots, and one blue daze (*Evolvulus glomeratus*), 1-quart size pot, where planted 6 inches deep in each bioretention cell. Phase II storm events used HLRs of 4.1 cm/h, 6.9 cm/h, and 13.9 cm/h (Table 2). Photographs of the bioretention cells during Phase I and Phase II are shown in Appendix A. Tracer studies before and after Phase I and Phase II were conducted to assess changes in the hydraulics of each system over the study period (data not shown). This allowed us to observe whether the plants and their roots could have affected system hydraulics over the course of the study.

3.3.4 Sampling and Water Quality Analyses

A 200-mL water sample of the inflow and outflow was collected at each sampling event at predetermined time intervals (every 20 or 30 minutes, depending on the storm event) and placed in acid washed high-density polyethylene plastic bottles. Bottles were immediately placed in a cooler containing ice packs and transported to the laboratory after each field experiment. Samples were then filtered through 0.45-μm-pore-diameter membrane filters and refrigerated according to *Standard Methods* (APHA et al., 2017).

Each water sample was tested for dissolved nitrogen species: total ammonia nitrogen (TAN, NH₃ + NH₄⁺), nitrate + nitrite (NOₓ-N = NO₂⁻ + NO₃⁻), and total N (TN). A subset of samples was tested for total dissolved organic carbon (DOC). NOₓ – N and TAN were measured by the gas
diffusion conductivity method using a Timberline Ammonia Analyzer (Timberline Instruments, Boulder, CO). TN was measured using two methods. For SE 1 – SE 7 and for SE 3-P - SE 4-P, TN was measured with HACH TN test kits (TNT plus 826 Method, Loveland, CO). Thereafter, TN and DOC samples were measured with a Shimadzu TOC-V CSH Total Organic Carbon/Total Nitrogen Analyzer (Shimadzu Scientific Instruments, Columbia, MD). The method detection limit for TN was 0.03 mg-N/L and 0.11 mg TOC/L for the Shimadzu instrument, 0.7 mg-N/L for the HACH TN test kits, and 0.014 mg N/L for NOx – N/TAN for the Ammonia Analyzer. DON was calculated by subtracting total inorganic nitrogen (TIN) from TN. On site temperature measurements of the influent and effluent water samples were made with a waterproof digital thermometer (Fisher Scientific, U.S.). A detailed quality assurance project plan was developed that included calibration with standards, duplicates, blanks and determination of method detection limits for all analytes.

3.3.5 Cost of Bioretention Systems

The cost of a bioretention system will depend on the size (surface area and depth), materials (if the materials are locally sourced or exported), and if volunteers are on hand to help. The two bioretention systems in this study cost $7,935. They were installed by CERES H2O Global Technologies from Sarasota, Florida (https://www.ceres-stormwater.com/), a professional company specializing in installing stormwater treatment technologies such as bioretention systems. The cost included excavation, installation, and initial planting. The modified bioretention systems have an additional layer, for the IWSZ, therefore they are deeper and required a deeper excavation and more materials. Note that due to the experimental nature of the pilot systems, this cost is higher than would be expected for full-scale bioretention systems.
Pazwash (2016) provides information on cost effectiveness of different BMPs and states an average cost of $7 - $15/ft³ of volume of runoff retained. A Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of conventional and modified bioretention systems by Xu and Zhang (2019) calculated costs for conventional and modified systems. They reported a mean annualized net present value (ANPV) of about $18,000 for a conventional system and over $105,000 for a modified system with a 30-cm IWSZ. The mean effective cost for a conventional system to remove 1-kg of TN (ANPV/FU1) was found to be approximately $2 and for a modified system with a 30-cm IWSZ approximately $6. Although the price decreased to $5 for a modified system with a deeper IWSZ of 60-cm.

3.3.6 Data Analysis

Weighted influent and effluent concentrations were used to determine the mass removal efficiency. We were not able to measure the flow rate out of the system and assumed the flow rate out of our lined system was equal to the flow rate in. However, moisture losses were not taken into account. Modeling the flow regimes through the cells using Hydrus-1D porous media software supported this assumption (data not shown)(PC-Progress, 2019). Statistical analysis was conducted using Microsoft Excel and the JMP Pro 13.2.1 statistical software package (SAS Institute, Cary, NC). One-way analysis of variance (ANOVA) test with a significance threshold set at 95%, α-value of 0.05, was used to determine significance of N removal between the two systems and groups of data. A Pearson correlation and Density Ellipse fit with a confidence level of 95% were used to determine linear correlations between two variables. Box and whisker plots were used to show the distribution of the removal of N species and DOC as affected by different variables.
3.4 Results and Discussion

3.4.1 Overall Performance of Conventional and Modified Systems

Average influent and effluent concentrations for all N species and DOC for both the conventional and modified systems over the entire study are shown in Fig. 2. Information on removal efficiencies for each storm event for TAN, NO$_x$-N and TN, along with HLR, storm duration, ADC, and number of pore volumes replaced in the IWSZ are shown in Table 2. Lower effluent N species concentrations were achieved in the modified bioretention system compared with the conventional system (Figure 3.3). On average, 3.12 mg-N/L of TN was introduced to both systems at a constant HLR for storm events that ranged from 2-6 hours. The weighted average effluent TN concentration for the modified system (0.74 mg-N/L) was significantly lower than for the conventional system (1.54 mg-N/L) (p-value=0.001). Significantly lower effluent concentrations of TAN (p-value = 0.0014) and NO$_x$ (p-value = 0.001) were also observed in the modified bioretention system effluent compared with the conventional system. NO$_x$ export (effluent concentrations higher than influent concentrations) was observed only twice in the conventional system, whereas the modified system always provided NO$_x$ removal, showing the effect of the IWSZ where denitrification occurs. Greater TAN removal in the modified system may indicate enhanced nitrification in aerobic regions of the IWSZ due to transport of oxygen during storm events. In addition, the modified system provided more stable effluent N species concentrations than the conventional system throughout the entire experimental program (note smaller standard deviations in Figure 3.3).

Although the conventional system investigated in this study achieved lower overall N removal than the modified system, the results were promising, better than field results in prior studies, even during Phase I when the system was unplanted (Bratieres et al., 2008; Collins et al.,
In particular, NOx removal in the conventional system when planted was higher (55%) compared to other conventional systems in the literature (-766% to 35%) (Davis et al., 2006; Dietz and Clausen, 2005; Hatt et al., 2009; Hsieh and Davis, 2005; Line and Hunt, 2009). The design of the conventional system, encased with an impermeable liner and with only a horizontal underdrain as the outlet, may have resulted in fully saturated portions of the bioretention cell during and right after a storm event, providing anoxic conditions for denitrification. In addition, denitrification in anoxic microsites in media aggregates occurs naturally during periods of high precipitation (Havlin, 2013; Parkin et al., 1987). Although no wood chips were included in the conventional system design, DOC was introduced in the influent, an average of approximately 4 mg-C/L, from the ground tree leaves used as a source of DON. In addition, organic carbon from decaying vegetation or animal excrement (e.g., cats, dogs, and chickens were observed at the site) were likely carried into these anoxic zones during natural storm events or in between storm events. The use of a liner and underdrain in conventional bioretention systems has the potential to reduce N contamination of the effluent to the groundwater even without inclusion of an IWSZ containing wood chips. The subtropical temperature at the field site and warmer influent temperatures may also have contributed to the high N removal observed, with an average effluent water sample temperature of 28°C (±1.9 °C) for both systems compared to other field studies in colder climates (LeFevre et al., 2015). Ergas et al. (2010) studied a modified bioretention system in northeastern Connecticut, U.S. treating agricultural runoff and documented poor performance in early spring when temperatures were cooler than later in the year with warmer temperatures. Microbial activity for nitrification in soils is optimal at temperatures within 20-35 °C (Manka et al., 2016; Russell et al., 2002).
Hydrolysis of the wood chips solubilizes the organic carbon and makes DOC bioavailable for denitrifying bacteria (Wang and Chu, 2016), however, export of DOC is not desirable. Export of DOC was detected during four out of eight storm events for the modified and three out of eight storm events for the conventional system. DOC export never exceeded more than 4.5 mg-C/L above the average influent DOC concentration. However, although average effluent DOC concentrations in the modified system (4.0 mg-C/L) were higher than those of the conventional system (3.4 mg-C/L), these differences were not significant (p-value = 0.56).

The field systems in this study were installed for two years before the experiments were conducted, which allowed sufficient time for the systems to stabilize and prevented leaching of DOC and DON at the magnitude typically encountered in new systems. Bench scale modified bioretention systems with short acclimation periods, from a few days to months, reported initial DOC and TOC values ranging from 50-114 mg-C/L, 10 to 50 times higher than what we observed in the field (Igielski et al., 2019; Lynn et al., 2015b; Peterson et al., 2015; Subramaniam et al., 2015). Calculations of denitrification kinetics in modified bioretention systems or other denitrifying bioreactors that use organic media can however be misleading if the systems have not reached stabilization. Subramaniam et al. (2015), who had a two-week stabilization period, observed that as the system aged, TOC concentrations decreased reaching a “second phase of stabilization.”

A bench scale study conducted in our laboratory (Lynn et al., 2015b) tested a 45-cm deep IWSZ layer with the same media as in this study’s field system and reported higher effluent TKN, NOx, TN, and DOC concentrations for storm events with similar HLR of 6.9 and 13.0 cm/hr. Export of TKN and DOC in the laboratory study was attributed to the dissolution of wood chips in the IWSZ. Similarly, Peterson et al. (2015) studied a 70-cm IWSZ at bench scale, more than
twice as deep as our IWSZ. Although they achieved TN and NO$_3^-$ removals of 60% and 82%, respectively, they observed an export of TKN attributed also to the wood chips. Overall, the field modified bioretention system with the shorter 30-cm IWSZ was more efficient at removing TKN and NOx than modified bioretention systems studied in the laboratory. Possible reasons for the improved efficiency may be because the two-year operation period before the start of the field experiments provided sufficient time for the wood chips to acclimate and stabilize or the presence of a more diverse community of microorganisms at the field site. A meta-analysis of 57 denitrifying bioreactors revealed that denitrification rates dropped significantly after the systems were in operation for a year but then stabilized (Addy et al., 2016). That meta-analysis supports the observation made by other shorter duration studies. Therefore, when natural organic materials are used as denitrification substrates, it is important to conduct long-term studies as hydrolysis of the wood chips and denitrification rates change over time (Robertson et al., 2008).
Figure 3.3 Average influent and effluent concentrations of nitrogen species (mg-N/L) and DOC (mg-C/L) for all storm events combined: unplanted Phase I and planted Phase II field experiments. Error bars represent one standard deviation.
Table 3.2 Overall mass removal efficiency for all storm events for the conventional and modified bioretention systems unplanted Phase I (SE1 – SE14) and planted Phase II (SE1-P – SE6-P).

<table>
<thead>
<tr>
<th>Storm Event ID</th>
<th>HLR (cm/hr)</th>
<th>Storm Duration (hrs)</th>
<th>ADC (days)</th>
<th>Number of IWSZ Pore Volume Replaced</th>
<th>Conventional Mass Removal Efficiency (%)</th>
<th>Modified Mass Removal Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TAN</td>
<td>NOx</td>
<td>TN</td>
<td>TAN</td>
<td>NOx</td>
<td>TN</td>
</tr>
<tr>
<td>Phase I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SE 1(^a)</td>
<td>6.9</td>
<td>4</td>
<td>0</td>
<td>2.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SE 2(^a)</td>
<td>13.9</td>
<td>2</td>
<td>7</td>
<td>2.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SE 3(^a)</td>
<td>4.1</td>
<td>2</td>
<td>4</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SE 4</td>
<td>13.9</td>
<td>2</td>
<td>6</td>
<td>2.2</td>
<td>83</td>
<td>-185(^b)</td>
</tr>
<tr>
<td>SE 5</td>
<td>6.9</td>
<td>4</td>
<td>12</td>
<td>2.2</td>
<td>81</td>
<td>44</td>
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<tr>
<td>SE 6</td>
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<td>8</td>
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<tr>
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<td>SE 10</td>
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<td>6</td>
<td>9</td>
<td>1.9</td>
<td>86</td>
<td>-14(^p)</td>
</tr>
<tr>
<td>SE 11</td>
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</tr>
<tr>
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<td>1</td>
<td>4.3</td>
<td>57</td>
<td>37</td>
</tr>
<tr>
<td>SE 13</td>
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<td>6</td>
<td>9</td>
<td>1.9</td>
<td>91</td>
<td>70</td>
</tr>
<tr>
<td>SE 14(^c)</td>
<td>6.9</td>
<td>6</td>
<td>5</td>
<td>3.2</td>
<td>56</td>
<td>47</td>
</tr>
<tr>
<td>Phase II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SE 1-P</td>
<td>13.9</td>
<td>4</td>
<td>13</td>
<td>4.3</td>
<td>81</td>
<td>26</td>
</tr>
<tr>
<td>SE 2-P</td>
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<td>0</td>
<td>2.2</td>
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<td>49</td>
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<tr>
<td>SE 3-P</td>
<td>13.9</td>
<td>4</td>
<td>9</td>
<td>4.3</td>
<td>74</td>
<td>56</td>
</tr>
<tr>
<td>SE 4-P</td>
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<td>6</td>
<td>4</td>
<td>1.9</td>
<td>85</td>
<td>61</td>
</tr>
<tr>
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<td>1.9</td>
<td>76</td>
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<tr>
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<td>Average</td>
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</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

\(^a\) Storm events SE1 - SE3 were run only for the modified bioretention system
\(^b\) Negative values in SE 4 and SE 10 represent an export of NOx in the effluent for the conventional bioretention system related to nitrification being the main process.
\(^c\) SE 14, values for TIN were used to estimate TN removal.
3.4.2 Effect of HLR on Bioretention System Performance

Typical N species concentration profiles during Phase I (unplanted) for both conventional and modified bioretention systems are shown in Figure 3.4 for high HLR (SE-11, 13.9 cm/hr) and Figure 3.5 for low HLR (SE-10, 4.1 cm/hr). At high HLR, the modified bioretention maintained low effluent N concentrations (< 0.5 mg-N/L) for approximately the first hour of the storm event, as the initial pore water was flushed out with the incoming stormwater (Figure 3.4b). After the pore water was flushed out, concentrations of all N species slowly increased until about 2 hours when effluent TN concentrations remained constant, between 2.1 and 2.6 mg-N/L, below the influent concentration of 3.8 mg-N/L. In comparison, the conventional bioretention’s N concentrations (Figure 3.4a) increased rapidly within the first hour and remained above 2.5 mg-N/L after 1.5 hours. By the end of the storm event, from 3.5 and 4 hours, the effluent TN concentrations in the conventional system were approximately the same as the influent.

At the lower HLR storm event of 4.1 cm/hr (Figure’s 3.5a and b), effluent TN concentrations in the modified system were below 0.5 mg-N/L for the duration of the six-hour storm event, when approximately one IWSZ pore volume was flushed out. For the conventional system, after 1.5 hours, TN concentrations began to increase and then remained constant at approximately 2 mg-N/L for the duration of the storm event. In the modified system, effluent TN concentrations remained below 0.5 mg-N/L from 30 minutes to the end of the six-hour storm event. The presence of the IWSZ in the modified system resulted in longer retention of the stormwater resulting in better treatment efficiency.

Summary data showing the effect of HLR on TAN, DON, NOx, and TN removal for all storm events for the conventional and modified systems are shown in Figure 3.6. TN removal for both systems was significantly higher (p-value < 0.05) at the lower 4.1 cm/hr HLR compared with
the higher HLR of 13.9 cm/hr. TN removal for the modified system in Phase I during the low HLR events can reach 90%, while at the higher HLR the TN removal was reduced to 52%. In contrast, the conventional system in Phase I achieved much lower TN removal; 59% during the low HLR, which decreased to 14% for the high HLR. For the modified system, mean TN removal rate over all storm events were 0.21 g/m²-hr (ranging between 0.08 and 0.42) during operation and as normalized to the cell area. TN removal rate was calculated by multiplying the change in weighted concentrations (influent – effluent) with the HLR for each storm event.

Although HLR had no significant effect on NOx in the conventional system (p-value>0.05), in the modified system NOx removal decreased significantly (p= 0.0003) as HLR increased from 4.1 to 13.9 cm/hr. In contrast, TN removal (Figure 3.6d) was significantly lower as HLR increased from 4.1 to 13.9 cm/hr for both systems (p = 0.003 for the conventional and p = 0.0007 for the modified system). Whereas the increase of HLR from 4.1 to 6.9 cm/hr was found to not be significant for either system (p-value>0.05), the increase of HLR from 6.9 to 13.9 cm/hr was determined to be significant (p=0.0003) for the modified system but not for the conventional system.

The effect of HLR on DOC is shown in Figure 3.7 for both systems. Note that DOC data is only available for eight storm events (SE 13-14 and SE1-P – SE6-P). DOC export was slightly higher for both systems at higher HLR (6.9 and 13.9 cm/hr); however, these differences were not statistically significant (p-value > 0.05). As discussed previously, effluent DOC concentrations were higher than influent concentrations for several storm events. Lynn et al. (2015a) performed a microcosm study using the same IWSZ medium and reported a DOC dissolution rate of $4.9 \times 10^{-3}$ mg DOC/g wood-h. This suggests that increased effluent DOC concentrations should be observed at longer HRT (i.e., lower HLR), but this was not observed in this study.
Designing modified bioretention systems to receive stormwater runoff at relatively low HLR can maximize N removal, as was shown in prior studies (Igielski et al., 2019; Lopez-Ponnada et al., 2017; Lucas and Greenway, 2011). This makes bioretention systems an ideal low impact development option to capture and treat small storm events that would contribute lower HLR’s. Another way this could be achieved is if bioretention systems are included in stormwater control retrofit projects in a “treatment train” with wet or dry ponds where the flow rate into the bioretention system can be regulated or in optimized stormwater systems with flow regulators that are adjusted based on expected precipitation.

3.4.3 Effect of Antecedent Dry Conditions on Performance

Prior laboratory studies (Kim et al., 2003; Lynn et al., 2015b; Smith, 2008) have observed a positive correlation of NOx removal with increasing ADC days (the detention time of the remaining stormwater in the IWSZ). The phenomenon was attributed to providing greater time for hydrolysis of the wood chips that contribute bioavailable organic carbon required to drive denitrification (Lynn et al., 2015b). DOC is either degraded or flushed out during a storm event and time is required for DOC to become bioavailable for the next storm event. Recent laboratory studies show how increased ADC directly impacts N removal, more specifically NOx (Igielski et al., 2019; Lynn et al., 2015b; Subramaniam et al., 2015). However, in our field study ADC was not statistically correlated with increased NOx or TN removal from the treated stormwater in either the conventional or modified system. A linear regression of ADC with NOx removal resulted in a low R² value of 0.0008 and a Pearson correlation coefficient of -0.07. A linear regression of ADC with TN removal also resulted in a low R² value of 0.0075 and a Pearson correlation coefficient of -0.092.
Figure 3.4 Nitrogen species profiles for: a) conventional bioretention system and b) modified bioretention system during a four-hour storm event (SE 11, unplanted) and HLR of 13.9 cm/hr.
Figure 3.5 Nitrogen species profiles for: a) conventional bioretention system and b) modified bioretention system during a six-hour storm event (SE 10, unplanted) and HLR of 4.1 cm/hr.
Figure 3.6 Box and whisker plots show the distribution of TAN, DON, NOx-N and TN removal for all the storm events (Phase I and Phase II) in the conventional bioretention (darker grey boxes) and modified bioretention (lighter grey boxes) systems as affected by HLR.
Figure 3.7 Box and whisker plots showing the effect of HLR on DOC mass removal efficiency for SE13 - SE14 and SE1-P - SE6-P. In this limited data set the minimum and maximum values are within the box, therefore no whiskers are shown. Negative values represent an export of DOC in the effluent.

DOC concentrations in the pore water of the IWSZ for eight storm events, representing initial conditions before the start of a storm event, were found to not be correlated with increasing ADC \((R^2 = 0.0006 \text{ and Pearson correlation coefficient } = 0.35)\). Data were examined for a subset of storm events where at least one IWSZ pore volume was replaced in the prior storm event, which would be a significant amount of runoff. The results still did not show a clear relationship of increased in N removal with increased ADC.

The success of the modified system in removing NOx is evident even after back-to-back storm events (i.e., ADC = 0 days). This contrasts with prior studies that showed that longer ADCs increased stormwater contact time and DOC dissolution, resulting in increased N removal (Igielski
et al., 2019). In this study, the average initial DOC concentration in the IWSZ pore water was ~3.5 mg-C/L and the average influent stormwater DOC was ~4.0 mg-C/L. It was likely that this was sufficient for denitrifying the relatively low NOx concentrations entering the IWSZ. In addition, effluent DOC concentrations were ~4.0 mg-C/L, indicating that DOC did not limit denitrification. Even though we did not observe the same clear relationships as observed in laboratory studies, designers may still want to size bioretention systems based on the contact time (which includes ADC).

The success of the modified bioretention system at low ADC compared to prior laboratory studies, may also have been due to favorable field conditions, such as warmer ambient temperatures. In addition, laboratory studies can single out ADC as a controlled variable, while in this field study variations in soil moisture, temperature, percentage of the IWSZ flushed from the previous storm event, and influent N concentrations from natural storm events influenced the results. Although contact time is important for removal of N, ADC (in terms of days) did not significantly impact N removal in this study. Therefore, more research is needed at field scale, including measurements of readily biodegradable DOC and dissolved oxygen, analysis of microbial communities present in the IWSZ to provide insights into the effect of ADC on N removal, and minimum pore water contact time in the IWSZ required for a target N removal objective.

3.4.4 Effect of Plants on Performance

The range of NOx and TN removal for both the modified and conventional systems in Phases I (unplanted) and II (planted) is shown in Figure 3.8. Mean mass NOx removal efficiency (Figure 3.8a) increased for the planted systems compared with unplanted systems for both modified (from 78% to 88%) and conventional bioretention (from 15% to 54%); however, these
differences were not statistically significant (p = 0.3542 for modified and p = 0.1650 for the conventional). TN removal followed similar patterns (Figure 3.8b); TN removal was not significantly higher when the systems were planted (p = 0.32 for modified and p = 0.128 for the conventional). Prior bioretention studies reported significantly higher N removal when plants were included and demonstrated the importance of plant species selection for increasing N removal (Lucas and Greenway, 2011; Payne et al., 2014; Zhang et al., 2010). Note that this was a short-term study (6 months) and plants did not have an opportunity to become established in the soil. In addition, the low-lying Florida friendly plants were selected by community members for their flowers and aesthetic appeal and ability to attract butterflies. The selected plants are considered low primary productivity and therefore N removal was not significantly enhanced by inclusion of the plants.

Less variability in NOx and TN removal was observed for both systems during Phase II (planted) compared with Phase I (unplanted). Standard deviations for the percent removal in the planted systems were much lower than for the unplanted systems. Standard deviation for NOx removal in the modified system was 24% of the mean when unplanted and decreased to 7% when planted. Decomposition of vegetation and organic matter during drying and wetting cycles between storm events releases DOC to the water (Holden 2005) and may substantially increase nitrate removal rates (Maxwell et al., 2019) for the modified bioretention. Likewise, for the conventional system, standard deviation for NOx removal decreased from 70% of the mean in the unplanted system to 17% for the planted system. When planted, there was no NOx export from the conventional system, as was observed on two occasions during Phase I (Figure 3.8a). When planted, average effluent concentrations for TAN in the modified were lower and for the conventional NOx concentrations were lower.
In both systems, plants enhanced denitrification due to readily available carbon in the rhizosphere from root exudates and sloughed-off root tissue (Havlin, 2013). Even if the sand layer is well-oxygenated compared to the anoxic conditions of the IWSZ layer, the microbiome of the rhizosphere allows for denitrifiers to exist near plant roots and thrive in anoxic microsites where oxygen diffusion is reduced (Havlin, 2013). This may explain the enhanced denitrification observed in the planted conventional system.

3.5 Conclusions

This research assessed the performance of field-scale conventional and modified bioretention systems to achieve N removal under varying HLR, ADC, and presence of plants, over a period of four years since the date of installation. Results confirm that the modified bioretention with an IWSZ containing wood chips can improve NOx removal and provide stable TN removal under various conditions compared with the conventional system. The bioretention systems, when loaded with constant TN influent concentrations of about 3 mg-N/L for the duration of a storm event, sustained effluent TN concentrations below 0.75 mg-N/L for the modified system and below 1.60 mg-N/L for the conventional system. In addition, the modified system slightly improved TAN removal compared with the conventional system. The major condition we tested that significantly (p-value < 0.05) affected TN and NOx removal was HLR, which directly impacts the contact time of the stormwater with the media during a storm event. The storm events with lower HLR of 4.1 cm/hr had the greatest removal of TN, while at the highest HLR of 13.9 cm/hr, the lowest TN removal was observed for both systems. ADCs between 0 up to 13 days for storm events did not have an apparent impact on the N removal efficiency of the systems. The addition of plants improved NOx and TN removal averages, although not statistically significant with a 0.05 confidence interval. The improved N removal appeared more noticeably for the conventional
system, with plants providing more stable effluent concentrations in both systems. Additional long-term field studies and modeling efforts are needed to improve our knowledge on how these systems sustain treatment of N over time and different seasons, and to provide more accurate insights on maintenance requirements, including the replenishment of wood chips.

Figure 3.8 Box and whisker plots showing range of NOx-N (a) and TN (b) removal in Phase I (unplanted) and in Phase II (planted) for the conventional and modified bioretention systems. The circle marker is an outlier.
Chapter 4: A Semi-Empirical Approach to Modeling
Modified Denitrifying Bioretention Systems

4.1 Introduction

Nitrogen (N), a nutrient essential for all human and plant life on earth, has become an important environmental pollutant in the last 50 years (UN Frontiers Report, 2018). More so, reactive nitrogen has become a concern for water quality managers, which can occur as dissolved species such as ammonium (NH$_4^+$), nitrite (NO$_2^-$), and nitrate (NO$_3^-$). When found in surface water bodies at too high of concentration, reactive nitrogen can contribute to eutrophication and hypoxic environments that can harm aquatic life. In addition, high concentrations of nitrate in water may cause “blue-baby syndrome” (methemoglobinemia) in infants or even adults with certain medical conditions (Galan, 2018). For this reason, the U.S. Environmental Protection Agency (USEPA) has set a maximum contaminant level for nitrate at 10 mg-N/L (USEPA, 2009). Recent studies have also found that long term exposure to nitrate levels as low as 0.87 mg-N/L in drinking water may cause colorectal cancer (Schullehner et al., 2018). Reducing N loads to surface water and groundwater has been partially achieved by managing point sources that contain reactive nitrogen with advances in removing or recovering N by centralized wastewater treatment plants (National Academies of Sciences and Engineering, 2019; Yang and Toor, 2017). However non-point sources, such as urban stormwater runoff, are significant sources of N.

A challenge in treating reactive N found in stormwater is that approximately 43-80% of N is in dissolved form, and dissolved N is highly mobile (Taylor et al., 2005; Li and Davis et al.,
2014). Therefore, to improve N removal, management of dissolved N in stormwater runoff has been a priority that has led to advances in bioretention designs. These include modified bioretention systems that include an internal water storage zone (IWSZ) with wood chips as a carbon source to promote denitrification (Lopez-Ponnada et al., 2017). A recent four-year field assessment of a modified bioretention system demonstrated a significant removal of dissolved total nitrogen (TN) (77%) compared to a conventional bioretention that only provided 44% TN removal (see Chapter 3).

Impacts from non-point nutrient sources, defined as stormwater runoff and baseflows, are evident as the category with the largest N loads to many surface waters. It is estimated that non-point sources contribute approximately $2 \times 10^6$ kg-N/year to the Tampa Bay, approximately 57.4% of the TN load to the bay (Greening and Janicki, 2006; Greening et al., 2014). With an increase in impaired surface water bodies in the U.S. because of inputs of excess nutrients and many studies addressing the lack of water quality in stormwater management, low impact development (LID) technologies have gained popularity as green stormwater infrastructure solutions that address both volume reduction of surface runoff and water quality (Collins et al., 2010; Hunt et al., 2012).

Installation of modified denitrifying bioretention systems can assist in removing N and other pollutants found in stormwater runoff, ultimately reducing nutrient loads to surface waters. However, these technologies are still fairly new to design and to regulatory practitioners. Thus, in order to facilitate the adoption of a new technology it not only needs to be demonstrated in the field but also useable design guidelines need to be provided. In the case of modified bioretention, design guidelines are especially needed for sizing the IWSZ (i.e., the denitrifying layer). Current manuals on design of LIDs and BMPs have not adopted bioretention systems modified to provide
enhanced nitrogen treatment (e.g. (Christchurch City Council, 2016; NJDEP, 2004; PGC, 1993; Rossman, 2015)). Similarly, popular stormwater and BMP modeling software, such as SWMM, SUSTAIN, MUSIC, and L-THIA-LID (reviewed in Table 4.1 along with other modeling software), do not provide the user with a modified denitrifying bioretention system as an LID option. Laboratory studies of woodchips as a carbon source for the IWSZ have been conducted and provided denitrification kinetic models (Table 4.2). However, the kinetic models have not been calibrated or validated with field data and have not been adopted yet by stormwater modeling software.

Therefore, to bridge this gap and guide practitioners in the design of a modified denitrifying bioretention system, a model was developed in this research that captures some of the most important nitrogen processes within the system but is not so computationally complicated. The semi-empirical model incorporates field, laboratory, and hydrological data to allow the design of a modified bioretention system to meet N removal targets. The model allows the latest research on modified bioretention to be easily accessible to practitioners. It can be used on its own and adapted by the user or used as an add-on for existing stormwater software.

Typically, a conventional bioretention system is designed based on: 1) capturing the first flush (i.e. one inch or 2.5 cm rainfall depth) of the impervious area or 2) for a design rain event, such as the 2-year average return interval (Hunt et al., 2012; Davis et al., 2009). The main issue with these two approaches are that the LID structure is not being optimized for N removal. The question then arises, what if a practitioner was to design an LID structure such as a modified denitrifying bioretention system to provide a targeted annual N load reduction (kg-N/yr), to achieve a target performance in terms of effluent water quality? This might allow for more streamlined regulations and incentives, such as credits for installing denitrifying bioretention
systems for N management over other stormwater control measures that do not provide water quality improvements as a benefit beyond flood control. The results of such a design tool may lead to increased implementation of modified bioretention systems that would improve environmental outcomes for nutrient-impacted watersheds, especially those that are N limited.

Accordingly, the goal of this study is to provide a semi-empirical model for sizing modified denitrifying bioretention systems to treat and remove a specific target goal of N runoff from a contributing impervious area. The objectives of the research are to: 1) develop an easy-to-use model based on empirical evidence of the local climate of the site (which includes event rainfall depth and antecedent dry conditions (ADC, also commonly known as antecedent dry period, ADP, and antecedent dry days, ADD)) and the denitrification kinetics expected to occur in the IWSZ (Table 4.2), 2) test and validate the model using field data from Chapter 3, and 3) demonstrate the outputs of the model for a case study scenario.

The model developed in this chapter treats TN as a lumped parameter and assumes that all TN removal occurs in the IWSZ. The model doesn’t take into consideration different N removal mechanisms (e.g., ammonification, nitrification, denitrification, biosynthesis) or processes occurring in different zones (e.g., the unsaturated zone). As described in Chapters 2 and 3, these processes are needed for TN removal in denitrifying bioretention systems. Therefore, this chapter provides a preliminary conceptual model and approach to modelling denitrifying bioretention systems. Addition of other N species removal mechanisms, calibration, and verification are needed prior to implementation of the model.
Table 4.1 Most commonly used stormwater management modeling software that support bioretention systems (Adapted from Liu et al., 2014) and denitrification models for modified denitrifying bioretention systems.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Capabilities</th>
<th>Application</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWMM</td>
<td>Hydrologic, hydraulic and water quality model with optional continuous simulation</td>
<td>Detailed analysis of a watershed with storage-focused LID. Water quality treatment is input by the user</td>
<td>Used to evaluate the hydrologic performance of bioretention systems in a watershed</td>
<td>Applications: (Lucas, 2010), (Masi, 2011), (Neilson, 2010), (Wang, 2013), (Aad, 2010) Download: USEPA</td>
</tr>
<tr>
<td>SUSTAIN</td>
<td>A framework for placement of best management practices in urban watersheds to protect water quality. Hydrologic and water quality modeling in watersheds and urban streams</td>
<td>Searches for optimal management solutions at multiple-scale watersheds to achieve desired water quality objectives based on cost effectiveness</td>
<td>Local-scale evaluation with simulations of individual BMPs and analyses of the impact of various combinations of practices and treatment trains on local water quantity and quality</td>
<td>Applications: (Shoemaker et al., 2009) Download: USEPA</td>
</tr>
<tr>
<td>Hydro-CAD *</td>
<td>Hydrologic model that uses a design storm methodology based on the curve number (CN) method to calculate runoff and detention pond routing with exfiltration option</td>
<td>Analysis of storage and infiltration based LID within a watershed. Calculate runoff volume and flow to a bioretention system. Calculate infiltration rate through a bioretention system.</td>
<td>Used to evaluate the hydrologic performance of a bioretention system</td>
<td>Applications: (Lucas, 2010), (Jacobson, 2011) Download: HydroCAD Stormwater Modeling</td>
</tr>
<tr>
<td>HEC-HMS</td>
<td>Model to develop standard hydrograph based on precipitation input</td>
<td>Detailed analysis for bio retention hydraulics and runoff retention</td>
<td></td>
<td>Applications: (Heasom, 2006), (Giacomoni, 2012), (He, 2011) Download: U.S. Army Corps of Engineers Hydrologic Modeling System</td>
</tr>
<tr>
<td>RECARGA</td>
<td>Hydraulic model for optional event and continuous simulation or design purpose</td>
<td>Simulates water table and soil-moisture profile</td>
<td></td>
<td>Applications: (Wisconsin Dept. of Natural Resources – B), (Carpenter, 2010), (Turney, 2010) Download: Wisconsin Dept. of Natural Resources</td>
</tr>
<tr>
<td>Model</td>
<td>Description</td>
<td>Simulations</td>
<td>Applications</td>
<td>Download</td>
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</tr>
<tr>
<td><strong>DRAINMOD</strong></td>
<td>Hydrologic model based upon agricultural field drainage, and treatment, a similar process to bioretention</td>
<td>Simulates water table and soil-moisture profile</td>
<td>Applications: (Brown, 2013), (Bechtold, 2007), (Youssef, 2005)</td>
<td>Download: NCSU Biological and Agricultural Engineering Dept.</td>
</tr>
<tr>
<td><strong>L-THIA-LID</strong></td>
<td>Simple rainfall-runoff model that uses NRCS Curve Number (CN) method and even mean concentration to calculate annual runoff and pollutant loads</td>
<td>Calculates pollutant load reduction based on an EMC and runoff volume reduction</td>
<td>Simulates reduction in runoff volume and pollutant loads with the use of LIDs for single lot to watershed scale</td>
<td>Applications: (Ahiablame et al., 2012) Download: Purdue University</td>
</tr>
<tr>
<td><strong>WinSLAMM</strong></td>
<td>Hydrologic model that uses a derived distribution based upon small storm hydrology to simulate performance of controls</td>
<td>Pollutant wash off calculated based upon land characteristics. Model traces pollutants from sources and predicts effects of controls</td>
<td></td>
<td>Applications: (Pitt, 2004), (Neilson, 2010), (Talebi, 2012) Download: PV &amp; Associates Version 10</td>
</tr>
<tr>
<td><strong>IDEAL</strong></td>
<td>Hydrologic model that uses a derived distribution to simulate performance of controls, for both quality and quantity</td>
<td>Process-based pollutant loading and treatment model, includes decay, settling, and infiltration, focused upon evaluation of a site before and after development</td>
<td></td>
<td>Documentation: (Hayes, 2008) Applications: (Alexander, 2011) Download: StormOPS</td>
</tr>
<tr>
<td><strong>WWHM</strong></td>
<td>Hydrologic model based upon HSPF adapted for control practice design using continuous simulation</td>
<td>Calibrated regional parameters for the 19 counties of Western Washington, Version 2012 includes modeling elements to more accurately model bioretention and other LID practices</td>
<td></td>
<td>Documentation: Clear Creek Solutions) Applications: (Beyerlein, 2011) Download: State of Washington Department of Ecology</td>
</tr>
</tbody>
</table>
Table 4.2 Studies of kinetic models for denitrification in internal water storage zone (IWSZ) employing wood chips.

<table>
<thead>
<tr>
<th>Kinetic Models for IWSZ</th>
<th>Description</th>
<th>Capabilities</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lynn et al., 2015</td>
<td>1st order kinetic model with a denitrification rate constant of 0.01 min(^{-1})</td>
<td>Kinetic model to determine N concentration after x hours</td>
<td>For research. Used to estimate N removal</td>
</tr>
<tr>
<td>Peterson et al., 2015</td>
<td>1st order kinetic model with a denitrification rate constant of 0.0079 min(^{-1})</td>
<td>Kinetic model to determine N concentration after y days</td>
<td>Used to determine that 2.6 days of HRT would remove N from 3 mg/L to &lt;0.01 mg/L</td>
</tr>
<tr>
<td>Lynn et al., 2017</td>
<td>Biokinetic model. Model incorporates wood chip dissolution and biological denitrification</td>
<td>Model predicts nitrate mass removal efficiencies</td>
<td>Compatible with existing stormwater modeling software such as SWMM. &quot;Practical tool for engineers to quantify nitrate removal as a function of biofilter characteristics as opposed to assumed removal efficiencies.”</td>
</tr>
<tr>
<td>Igielski et al., 2019</td>
<td>1st order kinetic model with a denitrification rate constant of 0.0011 min(^{-1})</td>
<td>Kinetic model to determine N concentration after y days</td>
<td>Used to estimate N removal given the design parameters</td>
</tr>
</tbody>
</table>
| Lopez-Ponnada et al., 2020 | Semi-empirical approach to model modified bioretention. Rainfall dependent model using the denitrification kinetics for the IWSZ from Lynn et al., 2015a and field data. | Determines the percent of rain events that can be treated 100% by the designed modified bioretention system. Also determines the estimated total N mass removed from the stormwater by the treatment of the bioretention system | Practitioners and designers will be able to use this model to:  
  - Estimate N removal loads  
  - Design bioretention systems for a targeted N removal efficiency  
  - Policy - Provide a pathway for administering credits for the use of LIDs  
  - Estimate N removal under different climate scenarios such as wetter years vs drier years or more frequent higher intensity rain events vs more frequent lower intensity rain events |
4.2 Methodology

4.2.1 Model Inputs

The model requires two site-specific inputs. The first is rainfall data for the site where the modified bioretention is planned to be constructed. The second input is the anticipated N loading for the bioretention’s contributing surface area. In addition, the preliminary bioretention dimensions (L, W, D) are required including the initial design depth of the IWSZ (see Chapter 2 for more details on components of the bioretention system).

4.2.2 Rainfall Data

Rainfall data for the field site (Chapter 3) was downloaded from the U.S. Geological Survey (USGS) website for USGS station #275917082222500, located at East Lake at Orient Road in Tampa, FL (USGS, 2019). This was the nearest USGS rain gauge to the field site and was used to determine the hydrological conditions of the site. The rain gauge collects data at fifteen-minute intervals with minimum rainfall detection limit of 0.01 inches. A continuous record of rainfall data from 2014 to 2018 (the period the bioretention systems were closely monitored in the field) was downloaded to capture the average of the hydrological differences in precipitation over an extended period. This equated to 644 original rain events over the study’s time period. Due to global changes in weather patterns such as El Niño and La Niña some years are wetter and other years drier.

4.2.3 Rainfall Data Analysis

Analysis of rainfall data was carried out using Microsoft Excel. For all the cells when there was no recorded rainfall, an entry of "0" was recorded. To separate rainfall events in the 5-year
record, a separation period of six hours was used. Thus, a rain event started with the initial
detection of rain and continued in time until a period of six consecutive hours of no rain was
encountered. This way each rain event had to have a minimum ADC of six or more hours with no
rain before the start of the next rain event. ADC in the model refers to the time between storm
events when there was no rainfall detected. An ADC of six hours was selected because it was
assumed to be the time necessary to reduce the influent NO\textsubscript{3}\textsuperscript{-} concentration in the IWSZ treatment
media by over 97%, assuming first-order kinetics with a rate constant of 0.58 hr\textsuperscript{-1} (Lynn et al.,
2015a). Note that Lynn et al. (2015a) described a batch microcosm study with synthetic stormwater
and fresh wood chips so denitrification kinetics may differ from full-scale bioretention
performance. The rate law for a first-order reaction is written as:

$$\frac{-dC}{dt} = kC$$ \hspace{1cm} (4.1)

where the minus sign indicates a decrease of NO\textsubscript{3}\textsuperscript{-} with time, C is the concentration (in this case
NO\textsubscript{3}\textsuperscript{-}) and \(k\) is the rate constant for the reaction with units of reciprocal time.

The integrated form of the rate law for conditions at time \(t = 0\) with the initial concentration
as \(C_0\) and a final concentration of \(C\) at time \(t\) can written as:

$$C = C_0e^{-kt}$$ \hspace{1cm} (4.2)

where \(C_0\) is the influent concentration, \(C\) is the effluent concentration at time equal to \(t\), \(k\) is the
first-order reaction rate constant (hr\textsuperscript{-1}), and \(t\) is the hydraulic retention time.

For each rain event, the associated rainfall depth (inches) and ADC (days) was calculated.
Once the rainfall record was analyzed, frequency distribution curves were developed for rainfall
depth and ADC for the five-year record (2014-2018). Figure 4.1 provides an example. The
frequency distribution curves are a visual method of seeing the distribution of the data.
Rain events that produced 0.01 - 0.04 inches (~1 mm) of rainfall depth were removed from the data set. Not all rain events recorded by a rain gauge produce runoff. This is due to interception, infiltration, and surface storage of a specific land use category (Akan and Houghtalen, 2003). This is true even for impermeable surfaces, such as pavement or asphalt, which contain microscopic depressions that hold a specific amount of water that would end up evaporating. The maximum amount of rain as initial abstraction was calculated using the Curve Number method by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) assuming an impervious surface, such as an asphalt parking lot (Akan and Houghtalen, 2003). A total of 169 rain events out of 644 original rain events in this study’s data set fell under this criterion which were removed from the final rain event data set. For model calibration, the hydraulic retention time (HRT) was adjusted subsequently by hand until the root mean square error for the modeled versus field experiment results were minimized. No other model parameter was adjusted.

4.2.4 Rain Event Runoff Volume

The rainfall data was divided into three scenarios, as shown in the logic model in Figure 4.1. The first scenario includes the rain events with a runoff volume less than or equal to the volume captured within the IWSZ. This is referred to as the pore volume (PV) for the remainder of this chapter. The second scenario includes all the rain events with a volume greater than one PV but less than or equal to the bioretention ponding basin volume, typically designed to capture the first flush or one inch of runoff. Finally, the third scenario includes all rain events with a runoff volume greater than the volume pertaining to one inch of rainfall at the site. The three scenarios were used to calculate the mass of N treated and subsequently removed from the aqueous phase because of the N-removing mechanisms that occur in a bioretention system based on the hydrological parameters of the site. The removal efficiency of nitrate was then calculated, as described below.
The Microsoft excel based model is available upon request by contacting the dissertation author: emmalopez@mail.usf.edu.

4.2.5 Nitrogen Load

An average annual nitrogen load was calculated using an event mean concentration from the literature. Table 4.3 includes various N concentrations expected in stormwater influent found in the literature for different nitrogen species and land use categories. An event mean concentration of 2.0 mg-N/L was selected to calculate the annual N load at the modeled site, in East Tampa.

In addition, each rain event was assigned a load of N which was weighted proportional to the number of ADC days. Rain events with larger ADC days were considered to have larger N loading than rain events with shorter ADC due to the accumulation of pollutants and leaf litter during the dry days. On the contrary, when it rains more frequently the impervious surface is washed off constantly with less time for pollutants to accumulate. This relationship is shown in Figure 4.3. The nitrogen mass loaded into the system (kg) for the 5 years was then multiplied by the ADC of the rain events divided by the total ADC of all the five-year data set.
Figure 4.1 Logic Model for Calculating Nitrogen Removal through a Semi-Empirical Approach to Modeling Modified Denitrifying Bioretention System

Assumptions:
- Area of bioretention is 5% of the contributing impervious surface, i.e., a parking lot. The bioretention cell is 6 ft² and parking lot is 120 ft².
- 1 PV is the depth of a rain event that produces volume equal to 1 pore volume of the IWSZ. 1 PV translates to 0.25", the rainfall depth that when it falls on the parking lot would produce runoff that makes up 1 pore volume of the IWSZ (71.4 L).
- Maximum rainfall depth that the bioretention ponding basin is designed to hold as a volume, typically designed to hold 1" of rainfall.
- Using denitrification kinetics from Lyon et al., 2015.
- During saturated conditions, at infiltration capacity, additional volume of stormwater that is passing through the bioretention system is being treated by approximately 12% assuming a HRT of ~13.5 minutes (based on tracer study).
- Total annual volume of runoff based on rainfall data.
- Total annual nitrogen load coming off from impervious area is calculated based on an event mean concentration value for TN.
Table 4.3 Literature nitrogen event mean concentrations expected in stormwater influent for various categories of land use.

<table>
<thead>
<tr>
<th>Land Use/Category</th>
<th>Median Concentrations (mg-N/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TN</td>
</tr>
<tr>
<td>Residential</td>
<td>2.64</td>
</tr>
<tr>
<td>Mixed</td>
<td>1.85</td>
</tr>
<tr>
<td>Commercial</td>
<td>1.75</td>
</tr>
<tr>
<td>Urban Runoff</td>
<td>2*</td>
</tr>
<tr>
<td>Combined locations</td>
<td>1.24</td>
</tr>
<tr>
<td>Parking lot</td>
<td>1.5</td>
</tr>
<tr>
<td>Urban Runoff</td>
<td>2.36</td>
</tr>
</tbody>
</table>

*Not stated if it was median

4.2.6 Removal Efficiency

**Scenario 1.** The rain events that produce runoff less than one pore volume are assumed to remain within the modified bioretention system for six hours or more until the next rain event. Considering the denitrification kinetics expected for the woodchip media used in the bioretention system studied here, approximately 97% of the nitrogen that is nitrified in the system (i.e., nitrogen converted to NO₃⁻) and reaches the IWSZ is expected to be denitrified into N₂ gas within six hours. Therefore, for all the light rain events that produce runoff that would displace some volume of the bioretention system’s IWSZ, the model assumes 100% N removal.

**Scenario 2.** The rain events that produce runoff greater than one pore volume but equal to or less than the ponding basin volume are expected to have less overall treatment of nitrogen
pollution. The additional runoff greater than one PV is expected to only receive partial treatment because of the shorter contact time the stormwater spends in the IWSZ compared to a longer contact time of six hours or greater. The time the runoff spends in the IWSZ was determined empirically through tracer studies conducted in the field during the field study described in Chapter 3. From data obtained from the tracer studies performed on the planted bioretention systems, on average, the time the stormwater runoff spent in the IWSZ with ponding conditions was 13.5 minutes. Using this value as time $t$ in Equation 4.2 and calculating the removal efficiency, results in a 12.2% estimated removal of influent N for the additional runoff volume.

**Scenario 3.** The runoff from a large rain event produces runoff greater than the ponding basin volume and only receives partial treatment, at an even lower removal efficiency than Scenario 2. This is because a percentage of the stormwater runoff does not receive any bioretention treatment and goes untreated. Similarly, as in Scenario 2, the stormwater runoff volume up to the ponding basin volume receives treatment with approximately 12.2% N estimated removal for a volume up to 1 PV, which is treated by 100%.

**4.3 Results and Discussion**

Frequency distribution curves of the rain events rainfall depth and ADC will be unique to each site. Therefore, they should only be used for construction of stormwater control measures at that site for the most efficient design of bioretention systems. Frequency distribution curves for the field site in East Tampa from 2014 to 2018 are shown in Figure 4.2. The frequency distribution curves show the frequency of different rainfall depths (Figure 4.2a) and ADC (Figure 4.2b) during the five-year period. As shown in Figure 4.2a, 83% of the rain events occur at rainfall depths of $\leq$ 1 inch, with the majority of the rain events with rainfall depths of 0.04 to 0.2 inches. Also, the majority of the rain events recorded in Tampa occur daily in the summer during the wet season.
Therefore, the majority of the rain events (60%) occur with short ADC of $\leq 2.5$ days as shown in Figure 4.2b, and 32% of the rain events with ADC $\leq 1$ day. Additional frequency distribution curves by year for rainfall depth and antecedent dry conditions are shown in Appendix B and Appendix C.

Figure 4.2 Frequency Distribution Curves of rain events from 2014-2018 in East Tampa, FL for a) rainfall depth (inches) and b) antecedent dry period (days).
Figure 4.3 Linear relationship of nitrogen load (mg) for rain events to the length of antecedent dry period (days).

4.3.1 Assessment of Model

When compared with field data experiments (described in Chapter 3), the model estimated lower N removal efficiencies than the field experiments. Field experiments, SE 9 and SE 3-P at the highest HLR and SE 4 and SE 13 at the lower HLR were used for calibration as described below. At the highest HLR, SE 9 and SE 3-P have rainfall depths of 1.09 inches, with average TN influent concentrations of 2.05 mg-N/L and 3.66 mg-N/L, respectively. The field experiments TN removal efficiency was 52% and 74%, respectively. The model reports a lower TN removal efficiency of approximately 32%. For smaller rain events in the field, SE 4-P and SE 13 had rainfall depths of 0.48 inches and influent TN concentrations of 2.57 mg-N/L and 3.12 mg-N/L, respectively. Removal for the modified system was 76% and 77%, respectively. While the model reports a removal efficiency of 58% N removal.

The model is sensitive to HRT, which is the term $t$ in Equation 4.2. The model initially assumed a constant HRT of 13.5 minutes for rain events greater than 1 PV, based on tracer studies
conducted at much higher HLR’s than the field experiments, approximately 32.4 cm/hr, when ponding in the systems was observed. In actuality, the HRT is different for each rain event and changes during a rain event. Ponding does not occur right away. Therefore, the model was calibrated by adjusting the HRT, by increasing it to account for the lower HLR’s encountered at the beginning of a rain event before the system reaches the time for ponding. Adjusting $t$ from 13.5 minutes to 100 minutes, approximately the average of the three HRT’s for the HLR’s tested in the field, resulted in a good fit of the field data as determined by the root mean square error (RMSE) of 9.62% (as shown in Table 4.4). Removal rates for the 1.09-inch rain event increased to 66% and for the 0.48-inch rain event N removal increased to 82%, which are much closer to the observations from the field experiment. The rest of the storm events conducted in the field were used for model validation as shown in Table 4.4. Model predictions for those storm events had a mean absolute percentage error (MAPE), which calculates the percent that the model is off from the field data, of 10.7%. Considering that TN field removal rates change every time in the field even at the same HLR as seen in Table 4.4 (standard deviation of 5% for the lowest HLR of 4.1 cm/hr and 9% for the highest HLR of 13.9), the model has a reasonably good fit.
Figure 4.4 Experimental Field Data vs. Modeled Data at five different rainfall depths.
Table 4.4 Model validation. Total nitrogen removal efficiency of field experiments along with model predictions and validation metrics. The different color rows represent storm events with HLR (cm/hr) of 4.1 green, 6.9 white, and 13.9 orange.

<table>
<thead>
<tr>
<th>Date</th>
<th>Storm Event</th>
<th>Rainfall Depth (in)</th>
<th>Field data TN Removal Efficiency</th>
<th>Model TN Removal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/2/2016</td>
<td>SE 3</td>
<td>0.24</td>
<td>80%</td>
<td>100%</td>
</tr>
<tr>
<td>3/17/2016</td>
<td>SE 6</td>
<td>0.48</td>
<td>90%</td>
<td>82%</td>
</tr>
<tr>
<td>4/29/2016</td>
<td>SE 10</td>
<td>0.48</td>
<td>88%</td>
<td>82%</td>
</tr>
<tr>
<td>8/10/2017</td>
<td>SE 5-P</td>
<td>0.48</td>
<td>87%</td>
<td>82%</td>
</tr>
<tr>
<td>1/18/2016</td>
<td>SE 1</td>
<td>0.54</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>3/8/2016</td>
<td>SE 5</td>
<td>0.54</td>
<td>89%</td>
<td>80%</td>
</tr>
<tr>
<td>3/24/2016</td>
<td>SE 7</td>
<td>0.54</td>
<td>77%</td>
<td>80%</td>
</tr>
<tr>
<td>4/7/2016</td>
<td>SE 8</td>
<td>0.54</td>
<td>75%</td>
<td>80%</td>
</tr>
<tr>
<td>7/21/2016</td>
<td>SE 14</td>
<td>0.54</td>
<td>87%</td>
<td>80%</td>
</tr>
<tr>
<td>4/24/2017</td>
<td>SE 2-P</td>
<td>0.54</td>
<td>81%</td>
<td>80%</td>
</tr>
<tr>
<td>8/16/2017</td>
<td>SE 6-P</td>
<td>0.54</td>
<td>87%</td>
<td>80%</td>
</tr>
<tr>
<td>1/26/2016</td>
<td>SE 2</td>
<td>0.55</td>
<td>65%</td>
<td>79%</td>
</tr>
<tr>
<td>2/9/2016</td>
<td>SE 4</td>
<td>0.55</td>
<td>63%</td>
<td>79%</td>
</tr>
<tr>
<td>5/5/2016</td>
<td>SE 11</td>
<td>1.09</td>
<td>59%</td>
<td>66%</td>
</tr>
<tr>
<td>5/19/2016</td>
<td>SE 12</td>
<td>1.09</td>
<td>73%</td>
<td>66%</td>
</tr>
<tr>
<td>3/27/2017</td>
<td>SE 1-P</td>
<td>1.09</td>
<td>79%</td>
<td>66%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HRT (min)</th>
<th>100</th>
<th>n</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean absolute deviation</td>
<td>MAD</td>
<td>8.07%</td>
<td></td>
</tr>
<tr>
<td>Mean Square Error</td>
<td>MSE</td>
<td>0.93%</td>
<td></td>
</tr>
<tr>
<td>Root mean square error</td>
<td>RMSE</td>
<td>9.62%</td>
<td></td>
</tr>
<tr>
<td>Mean Absolute Percentage Error</td>
<td>MAPE</td>
<td>10.7%</td>
<td></td>
</tr>
</tbody>
</table>

4.3.2 Case Study

As described in Chapter 3, the area of the modified bioretention system studied in the field is 6 ft². Following some of the basic design guidelines (Christchurch City Council, 2016; Metro Water Services, 2016) for sizing a bioretention system surface area (a 20:1 ratio or 5% of the impervious area to be treated) a 6 ft² bioretention system is designed to capture and treat rainfall from an impervious area of 120 ft². In this study, the 120 ft² area and 6 ft² bioretention system with
the 1-ft deep (30 cm) IWSZ was used as a case study for the model to determine the expected nitrogen load reduction and removal efficiency. The gravel-woodchip media had a 0.42 porosity (Lynn et al., 2015b), resulting in a pore volume of 71 L. Table 4.5 shows the results for this specific case. When the rainfall data were separated into the study’s three scenarios for calculating the N mass removed, the estimated removal for scenario 1 is 100%, for scenario 2 is 82%, and 44% for scenario 3. The N removal efficiency for all three scenarios weighted by the percent of storm events in each scenario resulted in a 83% removal efficiency.

Table 4.5 Estimated removal efficiency of modified bioretention system with a surface area designed to be 5% of the total impervious area. Three rain event (RE) scenarios based on the amount of runoff received at the location described as pore volume (PV). 1 PV = 0.25” of rainfall depth over the impervious surface.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Rain events in 5-year period</th>
<th>Percentage of all rain events</th>
<th>N load (kg) for all 5 yrs on system</th>
<th>N mass removed (kg) by system</th>
<th>N discharged into the environment (kg)</th>
<th>Expected Removal Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RE ≤1PV</td>
<td>187</td>
<td>39%</td>
<td>0.070</td>
<td>0.070</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>1 PV &lt; RE ≤ 1 in.</td>
<td>205</td>
<td>43%</td>
<td>0.077</td>
<td>0.063</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>RE &gt; 1 in.</td>
<td>83</td>
<td>17%</td>
<td>0.031</td>
<td>0.014</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>475</td>
<td>100%</td>
<td>0.178</td>
<td>0.147</td>
<td>81%</td>
</tr>
</tbody>
</table>

From the small 120 ft^2 impervious area representative of a single parking space or concrete pad in an urban area, approximately 0.178 kg of N is estimated to be loaded into the system over five years, with 0.147 kg estimated to be removed and 0.031 kg of N estimated to exit the system after the treatment. Rain events ranging from 1.01 inches to 7.27 inches only had partial treatment of the runoff volume, resulting in approximately 15,000 L of runoff that bypassed the bioretention
system. With this information practitioners can decide if their design meets the goals and standards for nitrogen removal for their site. If not, model users can adjust the size of the bioretention system to meet the mass N removal required for their site. For example, a deeper IWSZ can provide additional volume and hydraulic retention time which would allow greater overall N removal. Lynn et al. (2016) in fact observed greater NO$_3^-$ removal in deeper IWSZ column studies of 45 cm and 60 cm. In addition, increasing the surface area of the bioretention cell to the impervious area with a ratio of 1:15 (~6.7% of the impervious area) could also improve overall N removal.

Modified bioretention systems are ideal for locations with smaller storm events where the majority of the volume can be captured within the IWSZ. For example, in this case, the current size of the bioretention system captured 82% of all the rain events in the ponding basin, with 39% of rain events being small enough to capture 100% of the runoff within the IWSZ and provide maximum treatment. In addition, stormwater management with modified bioretention systems would be more efficient with continuous monitoring and adaptive control (CMAC) technology. An example of this technology is a smart integrated stormwater management approach that employs sensors and current and predicted weather conditions to respond automatically to environmental changes. In this case, a site with a treatment train of integrated stormwater technologies may release water from a stormwater pond or reservoir in advance of a rain event to make storage available for the incoming precipitation events. The water released from the stormwater pond can then enter a modified bioretention system at a specific flow and hydraulic loading rate allowing for longer hydraulic retention time to obtain greater overall nitrogen removal efficiencies. Using the semi-empirical model, a practitioner can determine the ideal size of the bioretention to maximize nitrogen removal.
4.3.3 Implication of Climate Change on Bioretention Design

When looking toward the future and accounting for changes in weather associated with climate change, the hydrologic predictions made by international teams of scientists include changes in precipitation duration, frequency, and intensity with more extreme weather events expected. For example, the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014), mentions that heavy rainfalls that occur in higher latitudes are expected to become more intense and frequent in the future. Flash floods are also projected to increase in parts of Southeast Asia, tropical Sub-Saharan Africa, and South America. In contrast, droughts are projected to intensify in some areas, especially in already dry regions (IPCC, 2014). Heavier rain events mean that there will be increased runoff in short periods of time. Although bioretention systems are known for attenuating peak flows, current systems designed prior to expected changes from increased global warming may not be equipped to retain the expected increased volumes which would ultimately result in decreased treatment. For example, in 2015 it was considered a very strong El Niño year in the Tampa Bay area, which represented wetter than average conditions, with the highest precipitation (79.29 inches at the Chapter 3 field site) of the five-year rainfall data set collected. The year before in 2014 was during a weak El Niño year (42.3 inches of precipitation). In 2015, approximately 21% of the rain events were higher than 1 inch whereas in 2014 only 14% of the rain events where higher than 1 inch. This indicates that not only was 2015 a wet year, the rain events were higher in intensity than the year before that had more storm events less than 1 inch.

The literature shows that a study involving using DRAINMOD to model hydrologic regimes of a bioretention system for projected climate change scenarios in Tennessee resulted in increased overflow events and higher total volume overflow from higher magnitude events (Hathaway et al., 2014). The overflow events occurred when the stormwater bypassed the
bioretention system and it went untreated, similar to scenario 3 in the case study in section 4.3.2. The researchers in that study highlighted the importance of increased surface storage and infiltration rate for resiliency of the systems to climate change. Their finding and those of Igielski et al. (2019) are also in line with the recommendations of this study for modified bioretention design; that is, to increase volume attenuation and increase HRT by: 1) restricting velocity through the IWSZ, 2) increasing the IWSZ volume, or 3) reducing the HLR.

Another impact of climate change for coastal areas such as Florida are rising sea levels. It is in fact projected that sea level could rise from 5 to 20 inches from current levels in the next fifty years in South Florida (SFWMD, 2009). For coastal communities and low-lying areas, this means groundwater levels are also expected to rise (SFWMD, 2009), which could impact allowable bioretention system depths, especially for deeper modified systems, that are built based on historical groundwater levels. Regional changes in climate can also be very different than global trends, therefore there are many significant uncertainties with the predictions. Areas with heavy rainfall are also tied to increased temperature changes, which could also improve denitrification rates due to increased microbial activity. For this reason, continued modeling efforts as more data becomes available will be useful for forecasting changes in climate to design bioretention systems to be as resilient to future changes as much as possible. In the meantime, bioretention systems equipped with sensors based on local weather can assist in preventing overflow volumes and water quality (Shen et al., 2020). Design recommendations based on typical design storms or criteria for base events such as capturing one inch of rainfall or the 10-year storm event based on analysis of historical rainfall data need to be modified to make the systems more resilient and account for change in climate.
4.4 Conclusions and Recommendations for Future Work

The goal of this study is to develop a semi-empirical model that can be used to design modified denitrifying bioretention systems for site-specific conditions. It is expected that systems designed using this approach will perform within targeted water quality standards. Not only would N removal efficiencies improve, benefiting environmental conditions, the model would allow for economic benefits. By appropriately sizing the bioretention systems for nitrogen removal, land area and resources for the construction and materials of these systems will be expended wisely.

The model will allow users to predict of N loads entering the environment after being treated by the modified bioretention system under various loading scenarios. For example, if the land use of a site changes or the impervious surface area increases and different N loads are expected, model users will be able to calculate the N loads expected by those changes. The model can also assist with watershed scale calculations to predict how many bioretention systems would be needed to remove a specific nitrogen load. In addition, with the predictions of the model for various scenarios, users will be able to be proactive and setup management action plans for the N not removed by the system if the bioretention systems don’t meet their target goals.

To the author’s knowledge, this is the first semi-empirical model for modified bioretention systems incorporating field data, denitrification kinetic data for the wood chip and gravel media in the IWSZ, and local weather conditions to estimate nitrogen removal. The model will be a useful add-in to stormwater management software (Table 4.1) currently lacking design guidelines for modified bioretention systems. Supported by all the empirical data, this model will provide estimates of nitrogen removal at an annual scale for modified bioretention systems in subtropical conditions. The model has the flexibility for users to adjust the denitrification kinetics if different media is used in the IWSZ and adjust the contact time if the hydraulic conductivity of the media
is different. With changes in climate, new rainfall data set forecasts can be used and analyzed in the model to determine the impacts of the nitrogen load on the environment and size bioretention systems accordingly. For example, rainfall data for an El Niño year can be analyzed to determine the N loads expected for that year. Lastly, the semi-empirical model is also user friendly so that users are not required to have a strong technical background. As long as they insert rainfall data for the site and know the size and budget available for installing a bioretention system, they can run the model and by trial and error determine a size that will meet their water quality goals.

Although the model was able to predict values close to experimental observations with metrics reporting less than 10% difference, the model had some limitations. For example, SE #3 in Table 4.4, which falls in scenario 1 of the model, had the largest difference between modeled and experimental values, as seen in Figure 4.4, where the model overpredicts. This is because of the assumption that all the N in runoff that enters the system is treated by 100%. Even though for field storm event SE #3, NOx was removed at 99.8%, there was NH$_4^+$ and Org.-N in the effluent which the model did not account for. The conditions assumed in the laboratory study of Lynn et al. (2015a) (100% stormwater is nitrified before entering the deeper IWSZ) which the denitrification kinetics are based on may not be the same as in the field. In addition, the batch study used by Lynn et al. used fresh wood chips compared to the acclimated system in the field study that had been exposed to environmental conditions for more than two years before the field experiments began. Even though six-hour intervals to determine a rain event are sufficient for NOx removal, the mechanisms for NH$_4^+$ removal and org.-N, occurring mainly in the sand layer, may be different. Another limitation is that the model does not account for the reality of a pollutograph, which has higher pollutant concentrations at the beginning of a rain event, and as a rain event progresses, pollutant concentrations decrease. The current model may be underestimating the
nitrogen removal, especially in scenario 3 when rain events are heavy and are greater than the ponding area. There is thus a volume of water that may bypass treatment through denitrification. Typically, the bioretention cell should be able to capture and treat the higher concentrations of the pollutant at the beginning (i.e. the first flush), but in this case because the model spreads out the nitrogen load over the whole volume, there may be greater N loads that bypasses the system than what may be occurring in actuality. Finally, another limitation of the model is because was calibrated using field data based on the experimental setup described in Chapter 3, it assumes that the runoff is applied evenly to the surface of the bioretention cell versus coming through a specified inlet which is the case most times. Having the stormwater applied evenly throughout the cell may allow for greater treatment than the case where effluent is routed from a specific inlet to a particular section of the cell where the water may infiltrate faster through preferential pathways, thus decreasing the treatment time. A summary of model developments that were not included and that would strengthen the current model include:

- Addressing the nitrogen load and removal of the different N species such as organic N, NH$_4^+$, and NO$_x$.
- Considering different N removal mechanisms, such as ammonification, nitrification, plant uptake, and biosynthesis. A discussion on the impact of plants in N removal is provided in Chapter 3.
- Finetuning N pollutant buildup and wash off based on ADC and rainfall depth to more accurately determine the N load for each rain event.
- Taking into account the HLR of each rain event.

It requires skill to provide a balance in modeling approaches and developing a model which is simple yet accurate. Ongoing research on modified bioretention systems, addition of N species
removal mechanisms, and calibration and validation with field data, are contributions that will allow the model to evolve. Many of the other stormwater models such as SWMM have evolved with the active participation and contribution of practitioners and researchers. It is hoped that the conceptualization of the semi-empirical approach to modeling modified bioretention systems will get to be implemented and adopted by practitioners for stormwater management to improve N removal.
Chapter 5: Community Engagement

5.1. Introduction

Service learning generally refers to the process of a student working with a community partner to provide a service based on mutually identified needs, while strengthening the community and contributing to a student’s academic experience through reflection and civic responsibility (Morgan and Streb, 2002; Sandaran, 2012; Torres et al., 2000). Service learning is also considered a high-impact practice for student learning (Brownell and Swaner, 2010; Kuh, 2008; Kuh, 2010). Given the requirement for a partner external to the university, service learning and community engagement (CE) go together. The Carnegie Foundation's Community Engagement Classification (CE Classification) is an elective classification that is based on voluntary participation by Institutions of Higher Education (IHEs) where community engagement is described as the collaboration between IHEs and their larger communities for the mutually beneficial exchange of knowledge and resources in a context of partnership and reciprocity (https://www.brown.edu/swearer/carnegie/about). The principles of Community Based Participatory Research (CBPR) (Israel et al., 1998), and culturally competent approaches for working with diverse communities (Briscoe et al., 2009), can also help guide community engagement for service learning initiatives.

Managing the nitrogen cycle, one of the 14 Grand Engineering Challenges (NAE, 2008), presents an opportunity to combine service learning and community engaged research. This is because as average population density increases, impervious surfaces increase, and thus infiltration
rates decrease and natural runoff pathways are altered. This is of particular concern in coastal communities in the U.S. where average population densities in coastal areas have more than doubled that of non-coastal areas (NOAA, 2004). Approximately 153 million people lived in U.S. coastal counties in 2003, a 33 million people increase since 1980 (NOAA, 2004). For many of these coastal areas in the U.S., managing nutrients in stormwater runoff remains a challenge. This is true for the Tampa Bay region, where nitrogen loads have decreased from approximately 10,000 to 5,000 ton/year since the 1970’s due to improvements made at wastewater treatment plants, while contributions from non-point sources, such as urban runoff, have grown over the same period from 16% to 62% of the total nitrogen loading (Greening and Janicki, 2006). Green infrastructure (GI), a suite of technologies that includes green (vegetative) roofs, rainwater harvesting, permeable pavement, grassy swales and filter strips and bioretention systems (USEPA, 2005; Dietz, 2007), work with nature to manage stormwater as close to its source as possible to promote the natural movement of water and maintain or restore a watershed’s hydrologic and ecological functions. Given the requirement to treat stormwater close to source, some green infrastructure requires implementation at the residential and community scale, and this requires partnerships with residents and communities. It is thus an excellent infrastructure to incorporate into service learning activities. In fact, there is an excellent example of integrating it with K-12 science and math curriculum (Locicero and Trotz, 2018; Locicero, 2015) and workforce development through the National Green Infrastructure Certification Program (https://ngicp.org/). In addition, for graduate engineering student researchers whose experimental field sites are located within a community, thesis and dissertation credits could be classified as service learning in situations where a strong community partnership exists, and if vouched as such when designing the research program.
Addressing the 21st century challenges for environmental engineering is also known to require paradigm shifts in education that promote service learning while incorporating culturally relevant activities that challenge students to develop solutions specific to socioeconomically disadvantaged and underserved communities (NASEM, 2019). While environmental engineering research in underserved communities has long been presented for global scenarios addressing water sanitation and hygiene as called for in the United Nations Sustainable Development Goals, the rise in meeting environmental challenges in disadvantaged communities in the U.S. is more closely tied with environmental justice (https://www.epa.gov/environmentaljustice).

5.2 Research Objective

The objective of this study is to demonstrate how green infrastructure research performed by a graduate engineering student, sited in a community and in collaboration with a community partner, can be integrated with service learning activities. Using her graduate experience that took place from August 2013 to May 2018, the following six qualities of service-learning were considered as described by Clevenger-Bright et al. (2012):

1. Integrative (academic and interpersonal growth)
2. Reflective (understanding deeper)
3. Contextualized (knowledge co-creation)
4. Strength-Based (partnership valuation and building on strengths)
5. Reciprocal (benefits to different stakeholders)
6. Lifelong (continual personal growth)
5.3 Methodology

5.3.1 Field Site, Partners, and Programs

As describes by Trotz et al. (2008), East Tampa is a landlocked area located within Hillsborough County, Florida (see Figure 5.1). It is contained by the physical boundaries of Interstate 275 to the west, Hillsborough Ave. to the north, 50th Street to the east and Interstate 4 to the south; making up 7.5 square miles. The area was incorporated into the City of Tampa in three separate annexations in 1911, 1923, and 1953; and has been a part of Tampa for over 50 years (Kitchen et al., 2004). It is a predominantly African American community, with 5,565 households, 84% of whom receive public assistance; the per capita income of the County is 2.3 times higher that of East Tampa residents. Stormwater from East Tampa drains directly to McKay Bay, an embayment of Tampa Bay that is impaired for dissolved oxygen and nutrients (USEPA, 2004). Residential land use has been found to contribute the largest percentage of N in the watershed, followed by transportation uses (USEPA, 2004). Therefore, research into the effectiveness of bioretention systems in this location has the potential to reduce nutrient loads to the bay (Locicero, 2015).
The Corporation to Develop Communities Inc (CDC) is an organization based in East Tampa whose goal is to improve the lives and spirit of the community. They achieve this by providing housing, real estate, job training and placement, and youth leadership programs to members of the community (CDC of Tampa, 2014). In 2000, the CDC successfully converted an abandoned bar on E. Lake Ave. into a 5,000 ft$^2$ Youth & Family Center with a computer laboratory and conference/training room that are used for workforce development programs, youth and family programs and offices for CDC’s administrative staff. This location, sold to a church in 2019, served nearly 1,000 children, parents and seniors annually, offering computer training, athletics, education, music, and art programs for local children. The urban area has mixed land use, with a church, car wash, and a laundromat located across the street, and two residential homes adjacent to it.

Through grants from the Tampa Bay Environmental Fund and the Environmental Protection Agency from July 2013 to June 2019, the University of South Florida partnered with the CDC to: 1) pilot bioretention systems in the East Tampa location of the Tampa Bay watershed, 2) develop workforce skills through the Tampa Vocational Institute (TVI) to design, install and
maintain bioretention systems, and 3) foster environmental stewardship with the Youth Leadership Movement Program (YLM). The TVI targets non-traditional adult learners; some trying to obtain their High School Equivalency Certificate (referred to as a GED) and some entering the workforce after serving time in prison. The CDC offers a six-week Green Construction workforce development program in which USF incorporated a green infrastructure curriculum with classroom instruction, field trips, tours of water and wastewater treatment facilities, and hands-on activities related to the design, installation, maintenance and monitoring of bioretention cells constructed for this project. The Youth Leadership Movement Program helps high school youth achieve success by focusing on obtaining their high school diploma, pursuing post-secondary education, and securing employment. Program elements include academic support, employability skills, leadership development, and giving back through community service.

5.3.2 Research Site Description

A bioretention system, consisting of two cells, was constructed during the week of November 11, 2013 at the Audrey Spotford Youth and Family Center. The cells were constructed by Grant’s Gardens of Sarasota Florida, with assistance from USF students, faculty, and students from the CDC’s TVI. The cells are located in a grassy area between the Audrey Spotford Youth and Family Center building and associated parking lot (Figure 5.2). These bioretention systems were used for a long-term field study comparing nitrogen removal without and with Florida friendly plants (discussed in Chapter 3), under varying hydraulic loading rates (HLRs) and antecedent dry conditions (ADCs) as described in Chapter 3. This site was also used for service learning activities, mainly with the CDC’s TVI and YLM programs, and where possible, these
activities were integrated with the development of the research site as part of a service learning experience for the graduate student in charge of the field research (Table 5.1).

Figure 5.2 Image of research site at the Audrey Spotford Youth and Family Center in East Tampa, FL, showing the bioretention cells, rain barrels, butterfly garden, mural, and educational signage.
Table 5.1 List of service learning activities conducted during the period of graduate research.

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Program</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/2/2013</td>
<td>Rain barrel workshop</td>
<td>YLM</td>
<td></td>
</tr>
<tr>
<td>11/11/2013</td>
<td>Construction of Bioretention Cells</td>
<td>TVI</td>
<td></td>
</tr>
<tr>
<td>7/1/2014</td>
<td>Painting of rain garden mural by the youth</td>
<td>YLM</td>
<td></td>
</tr>
<tr>
<td>07/1/2014- 7/2/2014</td>
<td>Painting of rain barrels</td>
<td>YLM</td>
<td></td>
</tr>
<tr>
<td>10/24/2014</td>
<td>Installed rain barrels</td>
<td>USF grad students</td>
<td></td>
</tr>
<tr>
<td>2/1/2015</td>
<td>Field trip to local wastewater treatment plant #1</td>
<td>TVI</td>
<td></td>
</tr>
<tr>
<td>2/1/2015</td>
<td>Field trip to USF #1 to view research laboratories</td>
<td>TVI</td>
<td></td>
</tr>
<tr>
<td>2/18/2015</td>
<td>Construction of rain garden at Mrs. Best house</td>
<td>TVI</td>
<td></td>
</tr>
<tr>
<td>3/13/2015</td>
<td>Community event showcasing LIDs at Mrs. Best house</td>
<td>TVI</td>
<td></td>
</tr>
<tr>
<td>4/1/2015</td>
<td>Field trip to local wastewater treatment plant #2</td>
<td>TVI</td>
<td></td>
</tr>
<tr>
<td>4/1/2015</td>
<td>Field trip to USF #2 to view research laboratories</td>
<td>TVI</td>
<td></td>
</tr>
<tr>
<td>7/30/2015</td>
<td>Installation of rain garden signage at the Spotford center.</td>
<td>TVI</td>
<td></td>
</tr>
<tr>
<td>8/7/2015</td>
<td>Planting and maintenance activity with youth #1</td>
<td>YLM</td>
<td></td>
</tr>
<tr>
<td>10/22/2015</td>
<td>Presentation at the joint meeting with TBRPC Agency On Bay Management and TBEP Technical Advisory Committee</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/13/2016</td>
<td>Planting of butterfly garden</td>
<td>USF grad students</td>
<td></td>
</tr>
<tr>
<td>7/15/2016</td>
<td>Planting and maintenance activity with youth #2</td>
<td>YLM</td>
<td></td>
</tr>
<tr>
<td>7/15/2016</td>
<td>Painting of Butterfly Garden sign</td>
<td>YLM</td>
<td></td>
</tr>
<tr>
<td>11/21/2016</td>
<td>Rain garden maintenance</td>
<td>YLM</td>
<td></td>
</tr>
<tr>
<td>4/6/2018</td>
<td>Tour of rain garden at the CDC with seminar speaker: Dr. Laura Schiffman (NRC Postdoctoral Research Associate, U.S. Environmental Protection Agency Cincinnati, OH)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/14/2018</td>
<td>Stormwater and raingarden activity #3. Maintenance of butterfly and rain garden. USF graduate students and professionals talked to the youth about engineering</td>
<td>YLM</td>
<td></td>
</tr>
<tr>
<td>5/29/2018</td>
<td>Tour of rain gardens site with representatives of the Florida Department of Agriculture &amp; Consumer Services</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the spring of 2014, a ten-week afterschool program was implemented at YLM to integrate topics of water awareness, green infrastructure, environmental stewardship, and the effects that humans have on the flow of water within the urban environment. This program included participatory research, stormwater management “hotspot” identification, installation of rain barrels, maintenance of current rain gardens and the communication of the project to various community members. The youth participants were guided through the Urban Stormwater Management Curricular Unit described above. A USF Environmental Science & Policy undergraduate, Shelby Mireles, worked with the YLM group.

In the summer of 2014, approximately 25 high school students attending the CDC summer camp at the Audrey Spotford Youth and Family Center participated in four days of stormwater management activities, which involved them learning about: 1) the natural and urban water cycle, 2) anthropogenic effects of stormwater on the Hillsborough River, 3) an introduction to stormwater management and rain gardens, 4) activity of painting four rain barrels, 5) installation of four personal rain gardens, and, 5) painting a mural designed by the students (Figure 5.3 left). Afterward, two of the rain barrels were installed by USF graduate students Laura Rankin and Emma Lopez-Ponnada. New plants species that are more colorful and pleasing were placed in the rain garden at the CDC Youth and Family Center along with a decorative fence to prevent people from entering the rain garden and stepping on the plants. These activities along with others performed as part of the service learning experience are listed in Table 5.1.

5.4 Results and Discussion

Reflections on events and activities during the service learning program are provided below by the researcher for the six qualities of service-learning that have been described by Clevenger-
Bright et al. (2012). The text that follows are personal reflections written in the first person by the author of this dissertation.

5.4.1 Integrative

The “integrative” quality of service learning focuses on how the student participates as both a learner and a community member succeeding both academically and interpersonally in the project (Clevenger-Bright et al., 2012). After having conducted research and participated with the CDC’s youth and TVI program, I created relationships with the community that will remain past the completion of this project. East Tampa is no longer a community I pass through on my way to downtown Tampa or St. Petersburg but a community I was invested in and want to continue working with to develop the needs and priorities that came up during our service learning activities. One of the needs that came up with the participants of the TVI program is the need for a trained workforce to construct green stormwater infrastructure. Another that came up with the youth program is the need for providing a space for urban farming and opportunities for students to learn how to garden and grow their own crops.

5.4.2 Reflective

The “reflective” quality of service learning is the process of reflection when the student critically reflects what they have learned during their service experience drawing a deeper understanding of their actions and experience and where they draw meaning and significance for future actions (Clevenger-Bright et al., 2012). Coming to the completion of my service learning through USF as a graduate student and looking back and reflecting on the activities and my opinions at the different stages of the experience, I am able to have a better understanding of community organizations. For example, I learned that community organizations are dependent on
the resources they have (e.g., their staff) to provide services for the community. At one point, I was becoming frustrated with our community partner due to what I perceived as a lack of interest but on reflecting on the situation realize there may have been a lack of resources and the CDC of Tampa was understaffed. This also brings up a point that when universities partner with community organizations, both need to assess that they have sufficient resources to follow through with their plans. The service-learning experience provided reflection for future actions that I would like to continue pursuing. For example, working with community programs such as the TVI to address the needs of communities with respect to stormwater management by training a workforce to install green infrastructure.

5.4.3 Contextualized

The “contextualized” quality of service learning encompasses the unique opportunity that service learning provides the student with access to knowledge and expertise found only in the context of community, connecting the knowledge gained in a classroom with the knowledge gained in practice, during the community engagement experience (Clevenger-Bright et al., 2012). I was able to contextualize the needs of a subset group of the community, the participants of the TVI program. These are adults looking to get back into the workforce looking for jobs to sustain their families. Even though they were in a construction class, I learned that some of the participants, after having worked with us on stormwater projects, were interested in starting their own landscaping business and providing these services to their communities and also surrounding ones.

More importantly, I learned about other critical infrastructure in these communities that provide transportation and education. For example, community members are interested in having rain gardens and rain barrels installed in their own home but many are not aware of how to install
them, who to call to install one for them, how much they cost, or of the sources available such as the Hillsborough Institute of Food and Agricultural Sciences (IFAS) extension office which provides free workshops where community members who attend and then receive a free rain barrel. Working with the community, made me aware that even if some of the community members would like to attend the workshop and get a free rain barrel they depend on public transportation which is poorly provided in Tampa and may not only be efficient in getting them to the training, but also may not be able to allow bringing the rain barrel home. The interventions to address stormwater management through these programs lack the awareness of communities with limited income and resources and don’t address their needs. Instead, these programs and workshops should be delivered directly in the communities and serve them close to where they live. One thought I had was that the CDC has an open air market, a roofed pavilion which is currently underutilized, that could provide the space to offer these types of events for community members.

![Image](image.png)

**Figure 5.3** First mural painted by the youth in 2014 (Left); and final product of the mural painted by a contracted artist from Miami (Right).

### 5.4.4 Strength-based

The “strength-based” quality of service learning focuses on the strengths and resources that reside in the community such as the expertise and capacity from community members and
organizations which serve as co-educators to the student (Clevenger-Bright et al., 2012). One of the strengths of the community of East Tampa are its board members. One of them is Mrs. Evangeline Best. Mrs. Best is a member of the community, 36 years retired social worker, a founding member of the East Tampa Neighborhood Organization Works and has served on the leadership board of the CDC of Tampa, and the East Tampa Community Revitalization Partnership (ETCRP) revitalization board as a chairperson for multiple terms. After the second cohort of TVI students were trained, I and this cohort of students installed the rain garden, gutters, and rain barrels in her backyard. Mrs. Best then hosted a community party in her house to showcase the green infrastructure to other community members as well as the partnership of the CDC with USF. She taught me and the TVI students the important role community members have as stakeholders to the green infrastructure projects we were conducting and helped provide buy-in from other community members who showed interest in these projects and protecting the local environment. Mrs. Best is also a resource of the history in her community and has taught me about the lessons she has learned working in multiple boards and partnering with other USF professors and students.

5.4.5 Reciprocal

The “reciprocal” quality of service learning encompasses the benefits offered and received by all the parties involved in the service learning experience (Clevenger-Bright et al., 2012). The activities with the YLM students provided them opportunities to learn about Florida friendly plants, harvesting seeds, gardening, an appreciation for nature and the environment, hands on activities related to stormwater projects. Also, the service learning experience provided an opportunity for the YLM and TVI students to engage with other USF graduate students, USF professors, Hillsborough county science and math teachers, and international students from Brazil who were part of a research for undergraduate student’s program. Reciprocally, I learned that for
many students this was their first time gardening and that they wished to be able to grow their own crops. I was even struck by one student, who happened to be there with his mother and younger sister, who enjoyed the gardening activity so much that he said this was more fun than being inside watching television. His comment really touched me and made me feel happy that the gardening activity I was conducting was bringing so much joy to him. Some students even asked me if they could take some of the gardening materials like gloves, shovels, or potted seeds home, which fortunately with the funds available they were able to take these tools home. Local urban garden initiatives are lacking in this community and would benefit among this group of the population who expressed interest in gardening and wishes to grow their own food.

5.4.6 Lifelong

The “lifelong” quality of service learning focuses on the lasting life experience provided by service learning which may impact the student in a distinctive, influential, and meaningful way (Clevenger-Bright et al., 2012). The service learning opportunity provided through my graduate research is immeasurable. It has changed me and impacted my vision for my career. All the moments experienced in the field and with community members were nuggets of gold that I gained by working in the community and that I would not have been able to gain in a laboratory setting or a classroom. It confirms my passion for working closely with community members, especially those with limited resources, to solve environmental problems and improve environmental conditions for people.
5.5. Conclusions

The integration of a university graduate research project with the youth and job training within the local communities provided a unique opportunity for research and education on green infrastructure for stormwater and nutrient management in the Tampa Bay watershed while addressing sustainable livelihoods. Once the bioretention systems were constructed, the site became a great asset to perform activities around it for the local youth, as was described in Table...
1, and to bring visitors of the Civil & Environmental Engineering department and programs to witness. The TVI and YLM students were paramount in developing the rain garden as a research and demonstration site; starting with the first cohort of TVI students who helped construct the wooden frame and underdrain for the two bioretention systems and installing the signage describing what a rain garden is Figure 5.4. The youth helped with the planting, maintenance, and painting the rain barrels as shown in Figure 5.5. The site would not have become a lively site to come to do research in if it wasn’t for the service learning with the youth and adults who were part of the research experience.
Chapter 6: Conclusions and Recommendations for Future Research

Managing reactive nitrogen (N) in stormwater runoff is essential to prevent nutrient overenrichment of aquatic systems which may pose a threat to water quality. Coastal ecosystems have suffered in the last 50 years from eutrophication and anoxic conditions leading to dead zones, attributed to the excess of nutrients. Many aquatic environments such as Tampa Bay, FL are nitrogen limited. Increasingly, non-point sources have become the largest contributor of pollutants to aquatic environment, with stormwater being one of the leading non-point sources of nutrients. Therefore, the effective management of stormwater with a focus on nitrogen is important.

Bioretention systems are a type of low impact development technology and considered a green stormwater infrastructure that has become widely used in many urban areas to capture runoff and treat it while providing aesthetic value and ecosystem services. Bioretention systems employ a series of engineered soil media that makes them efficient at removing particles, particulate phosphorous, metals, and hydrocarbons. When it comes to nitrogen removal, while conditions of conventional bioretention systems promote ammonification and nitrification nitrogen ends up being exported as NO$_3^-$, which is one of the reactive N species in aquatic systems.

Modified bioretention systems are designed to address this issue of nitrogen export by incorporating a denitrifying layer with wood chips called an internal water storage zone. This research was motivated by the need to study modified bioretention system in the field side-by-side
to a conventional system to determine the removal efficiency and provide design guidelines for implementation by practitioners.

This dissertation was divided in four primary chapters addressing the following research questions and associated research tasks:

- **RQ1.** What are the prior knowledge and research gaps in the literature pertaining to denitrifying wood chip bioreactors? RQ1 was addressed through a critical review of the literature presented in Chapter 2 on: 1) denitrifying bioreactors employing wood chip media used to manage residential non-point sources of nitrogen, 2) biodegradation of lignocellulosic material, 3) the effect of transient loading conditions on microbial processes, and 4) physical characteristics and operating conditions that impact design and performance is reviewed.

- **RQ2.** Is total N removal performance observed in the field greater in a modified lined denitrifying bioretention system when compared with a conventional bioretention system? As presented in Chapter 3, the side-by-side study of both systems allowed for a better understanding of the performance of each layer and the added benefits of incorporating an internal water storage zone to improve nitrogen removal. Modified bioretention systems provided approximately 77% TN removal while the conventional system provided a 44% TN removal. Most significant was NOx removal in the modified system, averaging 81% for all storm events compared to 29% NOx removal for the conventional. Since the systems were lined, the conventional system did not display nitrogen export like other studies. The liner may have allowed for areas of the conventional system to be saturated and provided a limited denitrification with the organic carbon from the influent. Lower hydraulic loading rates which translate to increased retention time improved N removal. The addition of plants also improved N removal, mainly due to plant uptake and increased microbial activity near the root zone. The
plants benefitted the conventional system the most, improving N removal similar to the removal efficiencies of modified system. Antecedent dry conditions did not impact N removal.

Figure 6.1 presents how well the field study bioretention systems compare with other LID technologies (Clary et al., 2017). The influent and effluent median TN concentrations achieved by a group of LIDs provided in the 2016 Summary Statistics report from the International Stormwater BMP Database (Clary et al., 2017) are plotted together with those of this field study. The figure shows the excellent TN removal by the study modified bioretention compared to the other LIDs including other bioretention systems, grass swales, and wetland basins. Even though influent concentrations in this study were approximately twice as high as those reported by the other LIDs at approximately 3mg/L, the modified median TN effluent concentrations where the lowest, at approximately 0.5 mg/L.

Figure 6.1 Median influent and effluent TN concentrations for Low Impact Development (LID) technologies provided by the International BMP Database along with the those of the field study for comparison.
**Recommendations:** Additional research on the long-term performance of modified bioretention systems will be useful for practitioners, especially the performance of the IWSZ and integrity of the wood chips. Research on smart integrated stormwater management is upcoming in urban cities. Incorporating continuous monitoring and adaptive control (CMAC) technology, employing sensors and current weather predictions to respond automatically to environmental changes, will improve the efficiency of bioretention systems within a network of other stormwater control measures. The addition of technology such as sensors would increase the maintenance on these systems and the need for a skilled workforce of operators to check on the sensors regularly and conduct routine maintenance on them. This could be a good opportunity to continue promoting training and funding for a green infrastructure workforce development and providing these new technical jobs in local communities. Many cities are voting for a stormwater penny tax which would fund stormwater initiatives, and in the future this may be a method to financially support this type of employment.

- **RQ3.** How can stormwater management models be improved to more accurately estimate N removal for modified bioretention systems in urban locations? **RQ4.** How can local stormwater practitioners design modified bioretention systems to address the nitrogen removal efficiencies needed in a local watershed to improve water quality conditions?

As presented in Chapter 4, a semi-empirical approach to modeling modified denitrifying bioretention systems was developed. The model simplified the N mechanisms that occur within a bioretention system and provided predictions of N loads (kg) removed and discharged into the environment annually. The model can be used on its own or as an add-on to popular stormwater management models that currently do not incorporate design guidelines or the implementation of modified bioretention systems in their models. Practitioners will be able to
design modified bioretention systems specific to the hydrologic conditions of the site by importing local rainfall data. The model employs denitrification kinetics for the gravel and woodchip media in the IWSZ and is calibrated with field data.

Recommendations: Developing the model further to include the nitrogen load and removal of the different N species such as organic N, NH$_4^+$, and NO$_X$ will make the model more robust. This will require considering different N removal mechanisms, such as ammonification, nitrification, and biosynthesis. Fine tuning the assumptions for N pollutant buildup and wash off based on antecedent dry period, in days, and rainfall depth will more accurately determine the N load for each rain event. Also, modeling the water flow through the different layers of the bioretention system with Hydrus 1-D would provide more accurate estimates of the hydraulic retention time of rain events. Finally, with the addition of these new parameters calibration and validation will be needed. The model can then be used to run case scenarios to determine impacts on the environment with changes in climate.

Stormwater management and implementation of green stormwater infrastructure to support it can result in many economic, environmental, and health benefits, and ecosystem services if designed and implemented properly. With the knowledge gained through this research, it is hoped that the adoption of modified bioretention systems will be made more accessible for designers, decision makers, and other practitioners. Being able to properly design a bioretention system to meet nitrogen removal targets may allow government agencies to provide incentives and credits for implementing these systems. Improvement of nitrogen treatment and removal from stormwater has been the main goal of this research in order to protect water quality and the health of our natural environment.
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Appendix A:

Bioretention Cells During Phase I (without plants) and Phase II (with plants)

Figure A.1 Bioretention cells at the field site without plants and with plants.
Appendix B:

Rainfall Depth Frequency Distribution Curves for Rain Events by Year

2014

2015

2016
Appendix C:
Antecedent Dry Condition Frequency Distribution Curves for Rain Events by Year

2014

2015
Appendix D:

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Long-term field performance of a conventional and modified bioretention system for removing dissolved nitrogen species in stormwater runoff

Author: Emma V. Lopez-Ponnada, Thomas J. Lynn, Sarina J. Ergas, James R. Mihelcic
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Appendix E:

CDC of Tampa Inc. - Photo Release Form

PHOTO RELEASE

I, ________________________________ (print guardian’s name) do hereby give CDC of Tampa, the
irrevocable right to use my child’s name (or any fictional name), picture, portrait, or photograph in all forms and
in all manners, without any restriction to changes or alterations (including but not limited to composite or
distorted representations or derivative works made in any medium) for advertising, trade, promotion, exhibition,
or any other lawful purposes, and I waive any rights to inspect or approve the photograph(s), including written
copy that may be created and appear in connection therewith. I agree that the photographer owns the
copyright to these photographs and I hereby waive any claims I may have based on any usage of the
photographs or works derived there from, including but not limited to claims for either invasion of privacy or
libel. I am of full age and competent to sign this release. I agree that this release shall be binding on me, my
heirs, and assigns. I have read this release and am fully aware of any right/claims that I am waiving.
I am the parent or guardian of the minor named below and have the legal authority to execute the above
release. I approved the foregoing and waive any rights in the premises.

PARENT SIGNATURE ___________________________ YOUTH SIGNATURE ______________________

REQUEST AND AUTHORIZATION FOR RELEASE OF RECORDS

I authorize the School District of Hillsborough County or ________________________________ to release
the following listed records of _________________________________ (print youth’s name)
to the CDC of Tampa for the purpose of educational planning for the above named student.
Type of records to be release:

☐ Academic
☐ Standardized Test Data
☐ Other (Please specify)

I have given my consent freely, voluntarily, and without coercion, after sufficient explanation of the subject
matter involved. This consent is subject to revocation at any time expect to the extent that the
program/individual, which is to make the disclosure, has already taken action in reliance upon it. This consent
shall be valid for a period of one year after the date signed.

PARENT SIGNATURE ___________________________ YOUTH SIGNATURE ______________________