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Low Impact Development Analysis and Comparative Assessment of Wet Detention Ponds with Floating Treatment Wetlands

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LOW IMPACT DEVELOPMENT ANALYSIS AND COMPARATIVE ASSESSMENT OF WET DETENTION PONDS WITH FLOATING TREATMENT WETLANDS

by

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ABSTRACT

The aim of this thesis is to examine, develop, and assess innovative best management practices (BMPs) in stormwater management for pollutant reduction, flood control, and environmental sustainability. Previous research has clearly shown that urban stormwater runoff quickly transports pathogens, metals, sediment, and chemical pollutants to receiving waterbodies, resulting in the degradation of receiving waters and disruption of ecological networks. In response to this growing concern, regulatory agencies, such as the Environmental Protection Agency (EPA) and the Florida Department of Environmental Protection (FDEP), have set forth regulations aimed at protecting and restoring waterbodies. These regulations include numeric nutrient criteria (NNC) and total maximum daily loads (TMDLs), which enable effective monitoring of a waterbody with regard to nitrogen and phosphorus pollution and help to restore waters not attaining their designated uses. Currently, many stormwater management systems do not provide sufficient nutrient reduction to meet growing regulations; thus, there is a clear need to develop additional BMPs to enhance nutrient reduction.

Firstly, this thesis provides an overview of BMPs used in urban regions across the globe to create networks of low impact development (LID), with a focus on policy analysis. Chapter 2 examines the regulatory policies in areas of the United States, Europe, Asia, and Australia from a federal, state, to local perspective in order to pinpoint what policies are supporting the shift from gray cities to green cities. Gray cities are cities comprised mainly of impervious surfaces, with little regard to the ecological health and hydrologic characteristics of the area. Green cities utilize LID to mimic pre-development hydrologic and ecological characteristics, resulting in a city that is both environmentally sustainable and offers many ecosystem services. The results of the global

policy analysis identified the policies and other factors, such as funding and public involvement, necessary to facilitate the shift from gray cities to green cities and support the widespread implementation of LID.

Secondly, this thesis provides a comparative analysis of three stormwater wet detention ponds, which all contained floating treatment wetlands (FTWs). FTWs are a new BMP, used to enhance nutrient reduction rates in stormwater wet detention ponds. FTWs are a manmade ecosystem, utilizing plants that grow on interlocking floating foam mats, that mimics natural wetlands. Both episodic (storm event) and routine (non-storm event) sampling campaigns were carried out at the three stormwater wet detention ponds located in Gainesville, Ruskin, and Orlando, Florida. The comparative analysis of the three stormwater wet detention ponds was based on two perspectives. The fist analysis, found in Chapter 2, focuses solely on the nutrient reduction potential of FTWs and how the installation of FTWs can be used to improve nutrient reduction rates in stormwater wet detention ponds. The second analysis, found in Chapter 3, focuses on the interaction between nutrients, microcystin, and chlorophyll-a in the stormwater wet detention ponds before and after installation of the FTWs. These two studies provide a holistic understanding of the environmental and ecological aspects of utilizing FTWs as a BMP in stormwater management. FTWs were found to have a significant impact on nutrient reduction rates in the three stormwater wet detention ponds, with total nitrogen (TN) reduction rates reaching 33% at the Ruskin pond during storm events and total phosphorus (TP) reduction rates reaching 71% at the Gainesville pond during storm events. Moreover, microcystin concentrations were found to have a negative correlation with nutrient concentrations, specifically total phosphorus, for both storm and non-storm events across all three ponds.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ABC	Active, Beautiful, Clean
BMP	Best Management Practice
CEDD	Civil Engineering and Development Department
CSO	Combined Sewer Overflow
DSD	Drainage Services Department
EPA	Environmental Protection Agency
FDEP	Florida Department of Environmental Protection
FDOT	Florida Department of Transportation
FFP	Free-Floating Plants
FTW	Floating Treatment Wetland
FWS	Free Water Surface
GDP	Gross Domestic Product
GI	Green Infrastructure
HAB	Harmful Algal Bloom
HK	Hong Kong
HSSF	Horizontal Subsurface Flow
IPA	Individual Parcel Assessment
LID	Low Impact Development
NDA	New Development Area
NELAP	National Environmental Laboratory Accreditation Program
NNC	Numeric Nutrient Criteria
NPDES	National Pollution Discharge Elimination System
NPPF	National Planning Policy Framework
NRDC	National Resources Defense Council
NWI	National Water Initiative

PUB	Public Utilities Board
SEA	Street Edge Alternatives
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
URA	Urban Redevelopment Authority
US	United States
VF	Vertical Flow
WSUD	Water-Sensitive Urban Design

CHAPTER 1: INTRODUCTION

1.1 Importance of Stormwater Management

Global population growth and degradation of freshwater resources has resulted in a global water crisis. Stormwater management is a key aspect of protecting our freshwater resources and ensuring future environmental sustainability. Expansion of urban developments and migration of people from rural areas to urbanizing regions has resulted in the formation of cities comprised mainly of impervious surfaces, with little regard to the ecological health and hydrologic characteristics of the area. These cities produce high quantities of polluted stormwater runoff and quickly transport pollutants to receiving waterbodies during rainfall events, resulting in the degradation of receiving waters. In response to this global issue, various best management practices (BMPs) have been developed to aid in stormwater management. BMPs are control techniques used to attain water quality and quantity goals in a cost-efficient manner. BMPs can be integrated into urban regions to create networks of low impact development (LID).

Various pollutants can be found in stormwater runoff that cause concern not only for environmental stability, but also for human health. Pollutants include pathogens, metals, sediments, nutrients, microcystin, pesticides, and many others. These pollutants originate from a wide variety of sources, including agricultural operations, automobiles, residential areas, animals, and industrial activities. If not properly managed, these pollutants are transported directly to receiving waterbodies where they can have detrimental effects on local organisms and ecological balances. The focus of this thesis is on the control and reduction of nutrients, specifically nitrogen and phosphorus species, found in urban stormwater runoff. The control of nutrients in urban stormwater runoff can be accomplished via the use of contemporary BMPs.

1.2 Low Impact Development for Stormwater Management in Urban Regions

LID can be defined as a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services (European Commission, 2013). LID can be used to manage stormwater runoff in urban regions in a manner that mimics pre-development hydrologic and ecological conditions. The incorporation of LID technology not only improves the hydrologic cycle but has also been shown to have societal and economic benefits. Many different BMPs can be integrated into urban regions to create networks of LID. Common BMPs used in urban areas to aid in stormwater management include greenroofs, permeable pavement, bioretention cells, and treatment swales. A summary of different BMP techniques used in urban regions is presented in Table 1-1 to Table 1-4.

Table 1-1. Summary of point based BMP technology

Best Management Practice	Description	Benefits
Retention basin  http://www.stormwaterpa.org	▪ A recessed area within the landscape that is designed to store and retain a defined quantity of runoff, allowing it to percolate through permeable soils into the groundwater.	▪ Reduces stormwater volume, which reduces the average annual pollutant loading that may be discharged from the system. ▪ Suspended solids, heavy metals, bacteria, pesticides, and nutrients are removed as runoff percolates through the soil profile.
Wet detention basin  http://www.facilities.vt.edu	▪ Wet detention systems are permanently wet ponds which are designed to slowly release a portion of the collected stormwater runoff through an outlet structure.	▪ Provides removal of both dissolved and suspended pollutants by taking advantage of physical, chemical, and biological processes within the pond. ▪ They are simple to design and operate, provide a predictable recovery of storage volumes within the pond, and are easily maintained.
Underground storage	▪ Underground storage and retention systems are special types of retention systems that capture the required treatment volume in an underground storage system.	▪ Used where land values are high, and the owner/applicant desires to minimize the potential loss of usable land with other types of retention BMPs.

Best Management Practice	Description	Benefits
 https://en.wikipedia.org		▪ Does not require human access for maintenance.
Vegetated natural buffers  http://ci.owatonna.mn.us	▪ VNBs are defined as areas with vegetation suitable for sediment removal along with nutrient uptake and soil stabilization that are set aside between developed areas and a receiving water or wetland for stormwater treatment purposes.	▪ An effective best management practice for the control of nonpoint source pollutants in overland flow by providing opportunities for filtration, deposition, infiltration, absorption, adsorption, decomposition, and volatilization.
Biofiltration systems  https://lacreekfreak.wordpress.com	▪ Typically, offline BMPs that are used when soils will not allow adequate percolation for retention systems. ▪ These systems incorporate soils, mulch, or other pollutant removal mixtures, along with an anoxic zone and planted vegetation to facilitate treatment and remove pollutants from the runoff.	▪ An artificial anoxic zone is created to facilitate improved nitrogen removal. ▪ The permanently wet zone serves as a source of water for plants. ▪ The system can be used adjacent to structures that may be adversely impacted by groundwater, such as building foundations and road foundations.
Rainfall interceptor trees  http://www.ims.gs	▪ Interceptor trees are those trees used in urban land uses adjacent to impervious surfaces as part of the stormwater treatment system to reduce runoff volume and pollution from the area.	▪ Reduces the volume of rainfall that lands on impervious surfaces and become stormwater runoff. ▪ This helps to reduce the total stormwater volume and pollutant loading entering the storm drain system and can reduce the size of downstream stormwater systems. ▪ Interceptor trees also provide for enhanced aesthetic value, provides shade to cool pavement and reduces surface runoff temperatures.

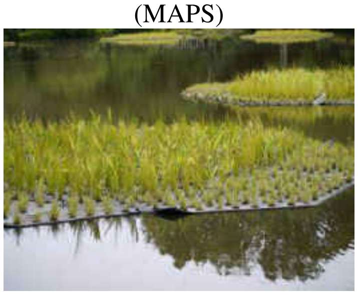
Source: Pinellas County Stormwater Manual, 2015

Table 1-2. Summary of linear based BMP technology

Best Management Practice	Description	Benefits
Exfiltration trench  http://www.palmettobay-fl.gov	▪ An exfiltration trench is a subsurface retention system consisting of a conduit, such as perforated pipe, surrounded by natural or artificial aggregate which temporarily stores and infiltrates stormwater runoff.	▪ Provides reduction of stormwater volume which reduces pollutant loads. ▪ Suspended solids, oxygen demanding materials, heavy metals, bacteria, some varieties of pesticides, and nutrients may be removed as runoff percolates through the soil profile.
Treatment swales  http://www.dot.ca.gov	▪ Have been used for conveyance of stormwater along roads for decades. ▪ When properly designed and maintained, swales can be used for stormwater treatment, providing retention and infiltration of stormwater.	▪ Provides reduction of stormwater volume which reduces pollutant loads. ▪ Suspended solids, oxygen demanding materials, heavy metals, bacteria, some varieties of pesticides, and nutrients may be removed as runoff percolates through the soil profile.

Source: Pinellas County Stormwater Manual, 2015

Table 1-3. Summary of area based BMP technology

Best Management Practice	Description	Benefits
Pervious pavement  http://nacto.org	▪ Pervious pavement systems include the subsoil, the sub-base, and the pervious pavement and include several types of designed systems such as pervious concrete, pervious aggregate products, pervious paver systems, and modular paver systems.	▪ Pervious pavement systems are retention systems and should be used as part of a treatment train to reduce stormwater volume and pollutant load from parking lots, or similar types of areas.
Greenroof/cistern  http://greencitygrowers.com	▪ A vegetated roof followed by filtrate storage in a cistern, which can be reused. ▪ The filtrate from the greenroof is collected in a cistern or, if the greenroof is part of a BMP treatment train, the filtrate may be discharged to a downstream BMP.	▪ The greenroof/cistern system functions to attenuate, evaporate, and lower the volume of discharge and pollutant load coming from the roof surface. ▪ Greenroof systems have been shown to assist in stormwater management by attenuating hydrographs, neutralizing acid rain, reducing volume of discharge, and reducing the annual mass of pollutants discharged.
Managed aquatic plant system (MAPS)  http://www.clemson.edu	▪ Aquatic plant-based BMPs which remove nutrients through a variety of processes related to nutrient uptake, transformation, and microbial activities. ▪ Examples include planted littoral zones and floating treatment wetlands.	▪ Can be incorporated into a wet detention treatment train to provide additional treatment and nutrient removal after the wet pond has provided reduction of pollutants through settling and other mechanisms that occur within the pond.

Source: Pinellas County Stormwater Manual, 2015

Table 1-4. Summary of other BMP technology

Best Management Practice	Description	Benefits
Stormwater harvesting  http://blog.farmsreach.com	▪ Uses treated stormwater for beneficial purposes before it is discharged to surface waters, thus reducing the stormwater volume and mass of pollutants discharged. ▪ It is most often used with wet detention as part of a BMP treatment train.	▪ Stormwater harvesting offers an alternative freshwater resource, which may alleviate demand on typical freshwater sources. ▪ Can be used to provide water for irrigation and other applications, thus reducing strain on groundwater aquifers, rivers, and lakes.
Natural area conservation  http://moverdubai.net/	▪ Protection of natural areas helps maintain the undeveloped hydrology of a site by reducing runoff, promoting infiltration and preventing soil erosion. ▪ Examples of conservation areas include areas of undisturbed vegetation preserved at the development site, such as forests, floodplains and riparian areas, steep slopes, and stream, wetland and shoreline buffers.	▪ Undisturbed soils and native vegetation in conservation areas promote rainfall interception and storage, infiltration, runoff filtering, and direct uptake of pollutants. ▪Natural areas are eligible for stormwater credit if they remain undisturbed during construction and are protected by a permanent conservation easement prescribing allowable uses on the parcel and preventing future development.
Disconnecting directly connected impervious areas  https://www.werf.org	▪ Directly connected impervious areas allow runoff to be conveyed without interception by permeable areas that allow for infiltration and treatment. ▪ Disconnecting impervious areas allows for infiltration and treatment of stormwater.	▪ Disconnecting impervious areas from roofs, small parking lots, courtyards, driveways, sidewalks and other impervious surfaces allows runoff to flow onto adjacent pervious areas where it is filtered or infiltrated. ▪ Disconnection of rooftops offers an excellent opportunity to spread rooftop runoff over lawns and other pervious areas where it can be filtered and infiltrated. ▪ Downspout disconnection can infiltrate runoff, reduce runoff velocity, and remove pollutants.
Eco-friendly landscaping  https://www.flickr.com	▪ Eco-friendly landscaping and fertilizers are now being promoted as a nonstructural BMP to reduce the need for fertilizers, pesticides, and irrigation through the Florida Yards and Neighborhoods and the Green Industry BMP program.	▪ This integrated approach to landscaping emphasizes nine interrelated principles: right plant, right place, water efficiently, fertilize appropriately, mulch, attract wildlife, manage yard pests responsibly, recycle yard waste, reduce stormwater runoff, and protect the waterfront.

Source: Pinellas County Stormwater Manual, 2015

Stormwater wet detention ponds are designed to hold a permanent pool of water that provides many beneficial uses including flood mitigation, pollution prevention, downstream erosion control, increased aesthetics, and recreational uses. These ponds are a common BMP for managing stormwater runoff in Florida and elsewhere. According to a summary of ten studies evaluating wet detention pond performance from 1982 to 2005, ponds in Florida were found to remove a mean value of 37% of total nitrogen (TN) and 69% of total phosphorus (TP). According to current Florida regulations, a stormwater pond shall achieve an 80% average annual load reduction of pollutants from the influent stormwater (F.A.C. Chapter 62-40). Currently the law pertains to solids removal only; however, recent research has indicated nutrients are the most significant parameters linked to water quality impairment within the State of Florida (Harper and Baker, 2007), and are ranked the first major source of impairment in Florida lakes (Obreza, et al., 2010). Stormwater wet detention ponds often receive heightened nutrient loadings, typically following large rainfall events, resulting in eutrophication of receiving waterbodies, harmful algal blooms (HABs), and deterioration of ecosystems and organisms. By incorporating additional BMPs within stormwater wet detention ponds, the effect of nutrient inputs can be mitigated; thus, decreasing strain on receiving waterbodies and improving overall stormwater quality.

1.3 Floating Treatment Wetlands

An innovative and emerging BMP for enhancing nutrient reduction in stormwater wet detention ponds is the installation of floating treatment wetlands (FTWs). FTWs are a manmade ecosystem that mimics natural wetlands (Sample et al., 2013). Plants grow on interlocking, floating foam mats, rather than at the bottom of the pond, which enables them to interact with suspended nutrients in the water column. FTWs support the growth of root systems of the floating plants, which offers a large surface area in the root zone for microbial nutrient removal processes (Govindarajan, 2008) and entrapment of suspended particles (Headley and Tanner, 2006). Pollutant reduction occurs through three primary mechanisms: 1) Plants directly uptake nutrients from the water using a process known as biological uptake; 2) microorganisms growing on the floating mats and plant root systems break down and consume organic matter in the water through microbial decomposition; and 3) root systems filter out sediment and associated pollutants (Sample et al., 2013). The choice of macrophyte species to plant on the floating mats often comes down to selecting locally present native species that exhibit vigorous growth within polluted waters under the local climate conditions (Headley and Tanner, 2006). FTWs offer an environmentally sustainable and economical approach for improving nutrient reduction in stormwater wet detention ponds. The cost of FTWs can range from $1 (homemade, recycled, or PVC products) to $24 (commercial/proprietary mats) per square foot. A cross-sectional representation of a typical FTW is presented in Figure 1-1 (Wanielista et al., 2012).

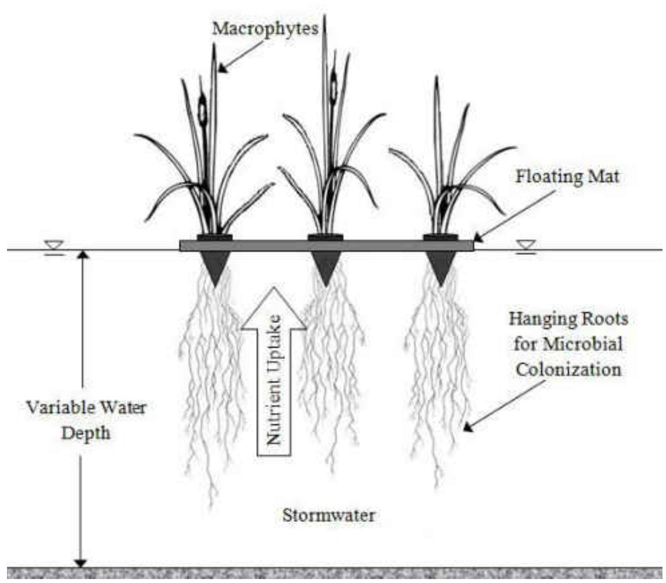


Figure 1-1. Cross-section of a typical Floating Treatment Wetland

1.4 Federal Regulations Governing Stormwater Management

The 1987 Water Quality Act added section 402 (p) to the Clean Water Act, requiring that the Environmental Protection Agency (EPA) issue National Pollution Discharge Elimination System (NPDES) permits for stormwater discharge. The NPDES Stormwater program regulates stormwater discharges from three potential sources, municipal separate storm sewer systems (MS4s), construction activities, and industrial activities (USEPA, 2012). This regulation laid the framework for stormwater management in the United States. Numeric nutrient criteria (NNC) are a critical tool for protecting and restoring the designated uses of a waterbody with regard to nitrogen and phosphorus pollution. These criteria enable effective monitoring of a waterbody for attaining its designated uses, facilitate formulation of NPDES discharge permits, and simplify development of total maximum daily loads (TMDLs) for restoring waters not attaining their designated uses (USEPA, 2016).

A January 7, 2014, ruling by the U.S. District Court for the Northern District of Florida allowed the EPA to withdraw and discontinue their NNC so Florida can implement their state-adopted, EPA-approved criteria to address nutrient pollution in Florida's waters. On September 17, 2014, EPA withdrew Federal criteria allowing the state of Florida's NNC to become effective as the only rules covering Florida's waterbodies (FDEP, 2013). FDEP's approach to regulating nutrients is set by a prioritization scheme which prefers site-specific analyses such as total maximum daily loads (TMDLs) and site specific alternative criteria, which are generally deemed superior to more broadly applicable interpretations of the NNC because of several natural factors which effect the expression of nutrient loading on a waterbody (FDEP, 2013).

1.5 Research Objectives

The research efforts of this study are to investigate the performance and interactions of FTWs installed in three stormwater wet detention ponds located in Florida. Insight into nutrient reduction potential and ecological impact, involving microcystin and chlorophyll-a, of FTWs will be obtained. In addition, a global policy analysis of LID will be conducted to investigate what policies and regulations are facilitating the shift to a more widespread use of LID techniques for stormwater management. Scientific outlines and questions pertaining to this study per chapter are as follows:

- Chapter 2 – Global policy analysis of LID and GI in urban regions. This chapter is aimed at assessing LID efforts and accompanying governmental policy from a global perspective. This study will provide a vantage on an evolving technology, where the best policies regarding construction, management, and regulation are still not known. This chapter will focus on case studies of LID technology and governmental policy for areas within the United States, Asia, Europe, and Australia. Moreover, this chapter will focus on identifying where LID is being successfully implemented and what are the accompanying supportive policies.
- Chapter 3 – Effect of FTWs on the control of nutrients in three stormwater wet detention ponds. This chapter is focused on the comparative evaluation of nutrient reduction, aimed at answering the following science questions: 1) Does the inclusion of FTWs improve nutrient reduction in stormwater wet detention ponds? 2) Are the three real world ponds (Gainesville, Ruskin, and Orlando) able to be compared based on initial nutrient concentrations? 3) If the initial conditions are

similar, is there a significant difference in the level of nutrient reduction with the inclusion of FTWs at the three stormwater wet detention ponds?

- Chapter 4 – Complex interactions among nutrients, chlorophyll-a, and microcystins in three stormwater wet detention ponds containing FTWs. This chapter attempts to answer the following science questions through a comparative evaluation of nutrient, microcystin, and chlorophyll-a concentrations: (1) How does the correlation among TP, TN, microcystin, and chlorophyll-a concentrations differ across the three candidate ponds? (2) Are these correlation values influenced by whether the sampling event is episodic (storm event) or routine (non-storm event)? (3) Does one nutrient species, either TN or TP, dominate the correlation factors with microcystin and chlorophyll-a? (4) Does the implementation of FTWs for enhancing nutrient removal in stormwater wet detention ponds affect correlation values?

1.6 Limitations

The limitations of this research are related to the climate conditions in central Florida and the surrounding areas. FTW studies were carried out from December 2010 to September 2011 at the Orlando pond. For the Ruskin and Gainesville ponds the study period spanned from December 2013 to April 2015. Further details on specific limitations with respect to the work conducted for specific devices are summarized at the end of each chapter.

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CHAPTER 2: GLOBAL POLICY ANALYSIS OF LOW IMPACT DEVELOPMENT IN URBAN REGIONS

2.1 Introduction

Global population growth and migration from rural areas to urbanizing cities has resulted in the creation of expanse urban regions and the formation of gray cities throughout the world. Gray cities are cities comprised mainly of impervious surfaces, with little regard to the ecological health and hydrologic characteristics of the area. Pollutants commonly found in urban regions are quickly transported by stormwater runoff to receiving waterbodies, with minimal treatment, following rainfall events. An inventive and evolving response to this global issue is the development of green cities, or cities designed to correct the ecological damage caused by today's gray society. Green cities utilize low impact development (LID) and green infrastructure (GI) to mimic pre-development hydrologic and ecological characteristics, resulting in a city that is both environmentally sustainable and offers many ecosystem services. Ecosystem services are the benefits provided by nature, such as food, materials, clean water, clean air, climate regulation, flood prevention, pollination, and recreation. These services are often treated as free commodities whose true value is not fully appreciated (European Commission, 2013).

LID is a successfully tested tool for providing ecological, economical, and social benefits through natural solutions. LID and urban green spaces provide people the opportunity to come in contact with nature, which has been shown to have psychological benefits by reducing stress, restoring attention, reducing criminal and anti-social behavior, and positively affecting self-regulation and restorative experiences (James et al., 2009). The incorporation of LID technology in gray cities not only improves the hydrologic cycle but offers benefits in the areas of soil, ecology, microclimate, and air. The aesthetic contributions of urban green spaces to city life are equally important. There is a plethora of theories and studies showing the preference amongst urban dwellers for urban areas with green spaces in them (James et al., 2009). An understanding of the multiple functions of LID is well developed; however, it is not well integrated into the policy, planning, design, and management of urban cities. The LID approach is summarized in Figure 2-1.

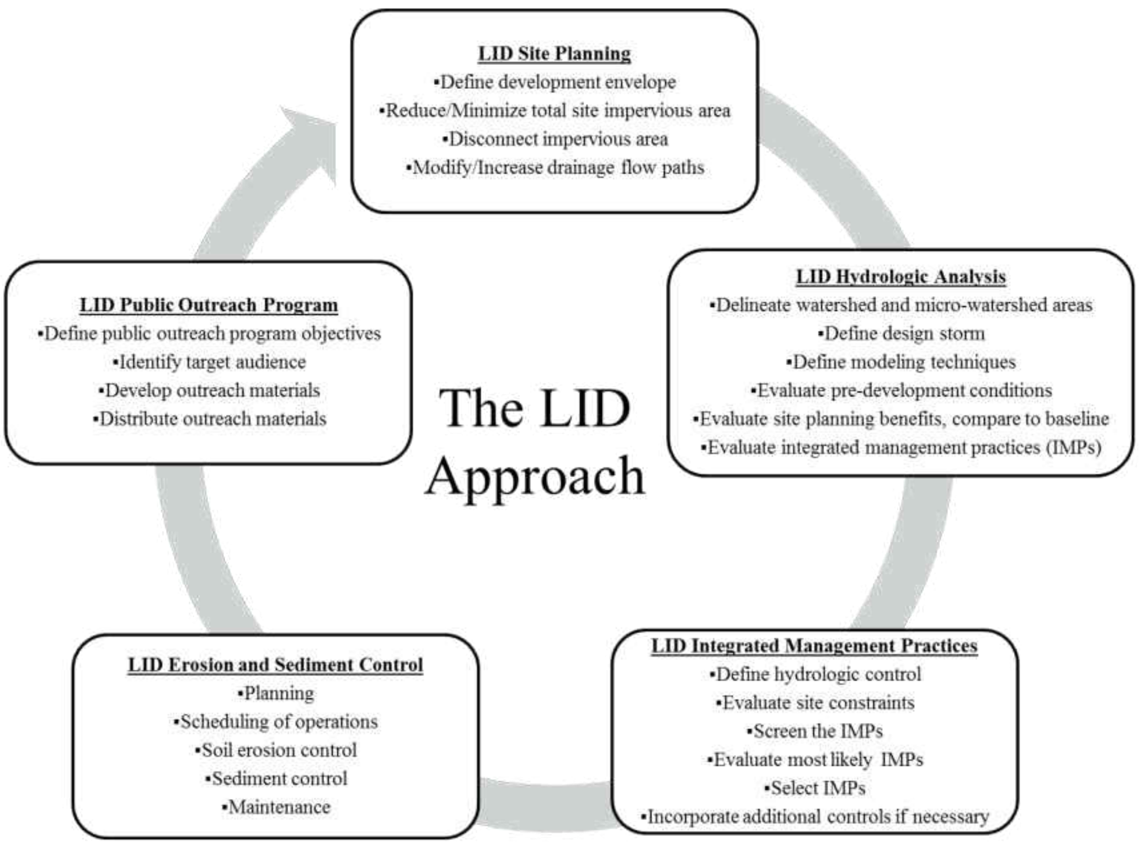

Figure 2-1. The LID Approach (Source: Handbook of Water Sensitive Planning and Design)

2.1.1 *Chapter Objectives*

This chapter is aimed at assessing LID efforts and accompanying government policy from a global perspective. This study will provide a vantage on an evolving technology, where the best policies regarding construction, management, and regulation are still not known. Case studies of LID technology and government policy for areas within the United States, Asia, Europe, and Australia will be presented. Moreover, this chapter will focus on identifying where LID technology is being successfully implemented and what policies are facilitating this movement.

2.2 Methodology

The global policy analysis was carried out by analyzing federal, state, and local stormwater codes within the United States, as well as stormwater regulations and policies for areas in Europe, Asia, and Australia. By analyzing LID projects at various scales along with accompanying government policy, a holistic understanding of LID was achieved. The current state of art in LID techniques is an evolving process; therefore, a proven foundation on which policies and regulations should be based upon does not exist. The comparative analysis of LID policies at a global scale lets one pinpoint where LID projects are being successfully implemented and what accompanying policies or incentives are supporting the movement.

Case studies of LID projects and policies were carried out for many cities within the United States, with a comparative analysis of cities utilizing combined sewer systems and separate sewer systems. The focus of case studies for Asia is on China. China has been a hotspot for LID innovation over recent years, after the government recognized the necessity of stormwater management for preventing catastrophic flooding events. The European Commission has recognized the benefits of implementing LID and GI for not only stormwater management, but also for societal and economic aspects. Case studies of LID include projects and policies in Germany and the United Kingdom. Germany is recognized as the birthplace of green roof technology and has taken the lead in developing and implementing LID techniques for stormwater management and improving the quality of life for its citizens.

2.3 Results and Discussion

2.3.1 *LID Technology and Policy in the United States*

The 1987 Water Quality Act added section 402 (p) to the Clean Water Act, requiring that the Environmental Protection Agency (EPA) issue National Pollution Discharge Elimination System (NPDES) permits for stormwater discharge. The NPDES Stormwater program regulates stormwater discharges from three potential sources, municipal separate storm sewer systems (MS4s), construction activities, and industrial activities (USEPA, 2012). This regulation laid the framework for stormwater management in the United States (US) for many years. Although section 402 (p) was a step forward in stormwater management for the US, its focus was on traditional stormwater management strategies. Regulations set by the US government led to the widespread use of more traditional, gray technology for the management of stormwater. Not until the 1990s did the idea of LID gain attention in the US. LID techniques were pioneered by Prince George's County, Maryland, in the early 1990s. Initially, LID was a radically different approach to conventional stormwater management and represented a significant advancement in the state of the art in stormwater management. The LID approach combined a hydrologically functional site design with pollution prevention measures to compensate for land development impacts on hydrology and water quality. The primary goal of this technology was to mimic the pre-development site hydrology by using site design techniques that store, infiltrate, evaporate, and detain stormwater (Prince George's County, 1999).

On April 19, 2007, the US EPA released the Green Infrastructure Statement of Intent, a collaborative effort among the signatory organizations to promote the benefits of using GI in protecting drinking water supplies and public health, mitigating overflows from combined and separate sewers, reducing stormwater pollution, and encouraging the use of GI by cities and wastewater treatment plants as a prominent component of their sewer overflow and MS4 programs (USEPA, 2007). Following this movement, many state and local governments gained interest in LID and GI, recognizing the ecological, hydrological, and societal benefits of the technology. In 2008, EPA released the Municipal Handbook, providing local governments with a step-by-step guide to growing GI in their communities. Most states are authorized by the EPA to implement the stormwater NPDES permitting program. EPA remains the permitting authority in a few states, territories, and most land in Indian Country (USEPA, 2016). EPA's NPDES permit requirements are often the primary driver for local stormwater codes. Individual cities may be issued a NPDES permit if their stormwater management plan is approved by the local state government. The EPA has developed the Water Quality Scorecard to help local governments identify opportunities to remove barriers, and revise and create codes, ordinances, and incentives, for improved water quality protection.

While there is interest in the multiple benefits of GI in the US, GI techniques have gained recent attention in relation to stormwater management. The Federal Clean Water Act Programs require local governments to overhaul stormwater management strategies to protect and improve surface-water quality (National Research Council, 2008). The Metropolitan Water Reclamation District of Greater Chicago has already invested $3.1 billion in a multiphase tunnel and reservoir plan to improve stormwater management (Buehler et al., 2011). Funding for stormwater management in the US is typically accomplished by charging all parcels or parcels of the same class, such as residential, the same rate. Funding for LID can be accomplished through stormwater fees, which generate a revenue stream to address the increasing investment most communities will have to make for stormwater management. Stormwater fees are often considered a fair, equitable method for charging people that benefit from stormwater infrastructure. Fee discounts and credits provide an opportunity for property owners to reduce the cost of their fees by using LID and GI techniques (USEPA, 2008). Examples of cities that have implemented stormwater fees include Philadelphia, Pennsylvania, Portland, Oregon, Toledo, Ohio, and Lenexa, Kansas.

2.3.2 *Case Studies within the United States*

2.3.2.1 Washington State

In Washington State, the Department of Ecology develops and administers the NPDES municipal stormwater permits. Washington State's Ecology Department has recently updated the state NPDES permit to require the use of practices that manage stormwater on-site and limit on-site imperviousness. In the past five years, Seattle Public Utilities has revised the City's Comprehensive Drainage Plan to address flooding and water quality needs through GI source controls, found in Seattle Municipal Code 22.800-22.808 (Seattle Public Utilities, 2015). The Seattle Street Edge Alternatives (SEA) Streets Project focuses on Broadview, a residential section of ultra-urban northwest Seattle, located in the Pipers Creek Watershed. The key elements of SEA Streets are drainage improvements, street improvements, landscaping, and neighborhood amenities. Landscaping and tree preservation provide rainfall management, runoff treatment, and aesthetic benefits. Vegetated swales, gardens, and bioretention areas are used in conjunction with traditional drainage infrastructure to collect and treat runoff close to the source. System designers combined traditional drainage features (culverts, catch basins, flow control structures, and slotted pipes) with interconnected swales, vegetation, and soil amendments to manage stormwater flow and discharge. The swales contain native wetland and upland plants to treat runoff and beautify the site. City engineers designed the system to reduce the peak discharge rate and volume from a two-year 24-hour storm event (1.68 inches) to pre-development conditions.

2.3.2.2 California

The NPDES Program has been delegated to the State of California for implementation through the State Water Resources Control Board and the nine Regional Water Quality Control Boards. Ordinance No. 181899, effective as of May 2012, was created to amend the existing Los Angeles Municipal Code to expand the applicability of the existing Standard Urban Stormwater Mitigation Plan requirements by imposing rainwater LID strategies on projects that require building permits (LA Stormwater, 2011). The main purpose of this law is to ensure that development and redevelopment projects mitigate runoff in a manner that captures rainwater on site, while protecting natural resources. The Trans-Agency Resources for Environmental and Economic Sustainability (TREES) created a demonstration site at a single-family residence in south Los Angeles. The Hall House site uses several of the selected LID strategies including a cistern collection system, redirection of roof-top runoff, vegetated/mulched swales, and retention grading to reduce runoff pollution. The swales, composed of recycled yard waste, slow the flow of stormwater, allowing for infiltration and pollutant removal. In addition, the yard is graded to direct runoff to depressed garden areas that also retain water until it can be absorbed into the ground. Most of the BMPs are relatively inexpensive and several are within the ability of the average homeowner to install (NRDC, 2015).

2.3.2.3 Comparison Across the United States

A summary of additional LID policy and initiatives for cities across the US is presented in Tables 2-1 and 2-2. The cities are broken into two categories, those cities that utilize a combined sewer system (Table 2-1) and those cities that utilize separate sewer systems (Table 2-2). A combined sewer is a sewage collection system that is also designated to collect surface runoff or stormwater. Combined sewers have been known to cause serious water pollution issues and environmental impacts during combined sewer overflows (CSOs), when rainfall causes the sewer to overflow and discharge untreated wastewater and stormwater into waterways. Combined sewer systems are typically not used in the construction of new cities for these reasons; however, they can still be found in many of the older cities across the US.

Table 2-1. LID policy and initiatives in sample US cities with combined sewer systems

Location	Description	LID Techniques	Flood Control
Philadelphia, Pennsylvania	▪ Implemented eight Land-Based Green programs to achieve their goals of reducing localized flooding, reducing combined sewer overflows (CSOs), and improving water quality, while also improving the quality of life of residents. ▪ The green roof project at the Fencing Academy of Philadelphia is a 3,000 ft^2 roof garden that makes use of natural processes to detain and treat a 2-year 24-hour storm event.	▪ Green roof ▪ Stormwater tree trench ▪ Stormwater bump-out ▪ Rain garden ▪ Rain barrel ▪ Pervious pavement ▪ Stormwater planter ▪ Flow-through planter	✓
Frederick County, Maryland	▪ A volume control approach allowed developers to replicate pre-development runoff patterns using micro-scale integrated management practices that capture and treat rainwater close to where it hits the ground. ▪ The use of LID enabled developers to eliminate the use of two stormwater management ponds and preserve 2.5 acres of undisturbed open space and wetlands.	▪ Rural roads ▪ Vegetated swales ▪ Undisturbed open space ▪ Wetlands ▪ Natural buffers ▪ Filter strips	✓
Portland, Oregon	▪ Portland's Bureau of Environmental Services initiated the Willamette Stormwater Control Program, providing technical and financial assistance for a number of pilot projects. ▪ The program focuses on LID techniques that capture runoff close to the source. These landscape practices enhance neighborhoods, reduce air pollution, and reduce flooding.	▪ Pervious pavement ▪ Green roof ▪ Rain garden ▪ Flow-through planter ▪ Vegetated swale ▪ Vegetated filter strip ▪ Extended dry basin	✓

Location	Description	LID Techniques	Flood Control
	▪ The Bureau will support 15 demonstration projects to retrofit existing commercial sites, industrial properties, schools, religious institutions, and apartment complexes.	▪ Constructed wetland ▪ Habitat preservation	
Seattle, Washington	▪ In Washington State, the Department of Ecology develops and administers NPDES municipal stormwater permits and now requires the use of practices that manage stormwater on-site and limit on-site imperviousness. ▪ Seattle Public utilities has revised the City's Comprehensive Drainage Plan to address flooding and water quality needs through GI source controls (Seattle Municipal Code 22.800-22.808).	▪ Bioretention ▪ Rain garden ▪ Pervious pavements ▪ Green roof ▪ Rainwater harvesting ▪ Vegetated swales ▪ Soil amendments	✓
New York City, New York	▪ The NYC Department of Environmental Protection is responsible for the city's drainage plan and stormwater management. ▪ The NYC Green Infrastructure Plan presents a "green strategy" to reduce CSOs into surrounding waterways by 40% by 2030. By managing the first inch of runoff from 10% of the impervious surfaces with LID source controls, CSOs will be reduced by 1.5 billion gallons per year, over the next 20 years.	▪ Rain barrel ▪ Bioretention ▪ Wetlands ▪ Pervious pavement ▪ Green roof ▪ Tree pits ▪ Gravel bed	✓
Atlanta, Georgia	▪ Ordinance 12-O-1761 was created to amend various sections of Chapter 74, Article X of the City of Atlanta Code of Ordinances for the purpose of promoting GI and runoff reduction practices. ▪ The Department of Watershed Management has updated the Post-Development Stormwater Management Ordinance to promote the use of GI on new and redevelopment projects in the city.	▪ Detention basins ▪ Curb cuts ▪ Vegetated islands ▪ Bioretention ▪ Directed rooftop runoff	✓
Chicago, Illinois	▪ In 2014, the City of Chicago released its Stormwater Management Ordinance Manual, which was created to provide the technical tools and guidelines necessary to comply with the Stormwater Ordinance and Chapter III of the Regulations for Sewer Construction and Stormwater Management. ▪ Announced a five-year, $50 million plan to make GI upgrades to roadways, streetscapes, and other public right-of-way projects.	▪ Green roof ▪ Vegetated swales ▪ Bioretention ▪Pervious pavement ▪ Rain garden	✓
Washington, D.C.	▪ DC Water has begun the implementation phase of the Clean Rivers Project, aimed at reducing the annual 2.5 billion gallons of CSOs to the Anacostia River by 98%. ▪ DC Water plans to explore a widespread installation of LID technology. On December 10, 2012, DC Mayor Vincent Gray signed the “Clean Rivers, Green District” Partnership Agreement that outlines a pilot GI program.	▪ Bioretention ▪ Street trees ▪ Landscape areas ▪ Pervious pavement ▪ Removing pavement ▪ Rain garden	✓

Table 2-2. LID policy and initiatives in sample US cities with separate sewer systems

Location	Description	LID Techniques	Flood Control
Dunnellon, Florida	▪ In October 2000, EPA authorized the Florida Department of Environmental Protection to implement the NPDES stormwater permitting program in the state of Florida (set forth in Section 403.0885, Florida Statutes). ▪ Issued Ordinance No. 2009-04, which states all buildings and sites shall be designed to incorporate green building and development technologies that include on-site stormwater management through LID techniques.	▪ Grass swale ▪ Bioretention ▪ Pervious pavers ▪ Rain barrel ▪ Cistern ▪ Green roof ▪ Rain barrel ▪ Underground storage	✓
Boulder, Colorado	▪ A "closed loop" landscape was created at the Environmental Center of the Rockies that captures and treats runoff on-site instead of conveying it to city waterways. ▪ The system uses integrated management practices such as retention grading, vegetated swales, and bioretention cells to capture and treat runoff, cleansing up to one-half the volume of a 100-year flood event.	▪ Drought resistant plants ▪ Retention grading ▪ Vegetated swale ▪Bioretention ▪ Rain garden ▪ Water harvesting ▪ Native vegetation	✓
Dallas, Texas	▪ The City of Dallas is required under Texas Pollutant Discharge Elimination System to develop and implement a comprehensive stormwater management plan. ▪ Permit Reference (Part III.B.b.i-ii) states an integrated stormwater management planning and design process evaluate LID and GI controls which mimic pre-development hydrologic flow conditions and provide passive water quality treatment.	▪ Pervious pavement ▪ Bioretention ▪ Green roof ▪ Grassy swale ▪ Infiltration systems	✓
Los Angeles, California	▪ The NPDES Program has been delegated to the State of California for implementation through the State Water Resources Control Board and the nine Regional Water Quality Control Boards. ▪ Ordinance No. 181899, effective as of May 2012, was created to amend the existing Los Angeles Municipal Code to expand the applicability of the existing Standard Urban Stormwater Mitigation Plan requirements by imposing LID strategies on projects that require building permits.	▪ Driveway cross ▪ Gravel swale ▪ Dry well ▪ Pervious pavement ▪ Planter box ▪ Rain barrel ▪ Rain garden ▪ Vegetated swale	✓

Flooding is a major concern for many US cities, especially those with aging infrastructure or are prone to heavy rainfall. One way of coping with the threat of urban flooding is through the National Flood Insurance Program. The National Flood Insurance Program aims to reduce the impact of flooding on private and public structures by providing affordable insurance to property owners and encouraging communities to adopt and enforce floodplain management regulations (FEMA, 2015). These efforts help mitigate the effects of flooding and reduces the socio-economic impact of disasters by promoting the purchase and retention of general risk insurance. Although the National Flood Insurance Program is beneficial, it does not address the underlying cause of urban flooding, which is inadequate infrastructure and infiltration capacity to manage stormwater. Flood insurance is purchased out of fear of personal or private property being damaged during a flood event and not having the resources to repair or replace it. For urban areas where the primary cause of flooding is inadequate infrastructure or infiltration capacity, money paid for flood insurance could be redirected toward promoting and implementing LID; thereby, minimizing the risk of flooding and lessening the obligation for property owners to purchase flood insurance. This line of thinking follows a proactive solution where the risk of flooding is reduced by detaining and infiltrating stormwater at the source with LID techniques; while, purchasing flood insurance follows a reactive solution where the risk of flooding is accepted and funds are used to repair or rebuild following a flooding event.

2.3.3 *LID Technology and Policy in Asia*

The massive population migration in China, characterized by people migrating from less developed cities, towns, and villages to urbanizing cities, was initiated by the Market Reform in the 1970s. Urban villages provided the ideal housing to migrants who could not afford market-rate housing within cities, or housing was simply not available due to high demand. The rent fees and living expenses were much lower in urban villages than the average costs in the city. Urban villages are the primary form of urban informal settlements in China and are marked by a high ratio of migrant population, high building density, and inadequate infrastructure. One of the main environmental problems in urban villages is inland flooding, which has been widely mentioned in recent years, especially in Beijing. The major reason for inland flooding is the high impervious paving percentage and the fragmented drainage pattern, caused by spontaneous building developments. The highly-developed urban environment does not support the natural stormwater cycle and aging drainage utilities are not adequate for their current usage. Moreover, global climate change has affected the intensity of precipitation, so much that daily precipitation in summer 2012 reached a new historical high in Beijing (Tong, 2014). One strategy for regenerating urban villages is the incorporation of GI, not only to increase the sites capability of infiltrating stormwater, but also to improve the site resilience of recovering from disaster. Greenroofs are an important strategy within urban villages as they can increase the infiltration area, purify pollutants, and slow the flow of stormwater. In such dense environments, there are many human activities happening; therefore, GI should provide services in addition to stormwater management. Community gardens not only help filter and infiltrate stormwater, but can also create outdoor open spaces and bring economic benefits to urban villages (Tong, 2014).

Since 2000, nearly half of all new buildings in the world were constructed in China (Jin and Alyas, 2008). The first International Green Building Conference took place in 2005. In 2006, China released the Green Building Evaluation Standard, a national green building standard, and in 2008, released a building labeling system, the Chinese Green Building Evaluation Label. The Natural Resources Defense Council (NRDC) helped China to develop the national standard and local green building guidelines through the Agenda 21 project, as well as the first LEED gold certified building in China, the Beijing Olympic Village.

2.3.4 *Case Studies within Asia*

2.3.4.1 Beijing

In Beijing, the urbanized environment does not provide enough infiltration, therefore inland flooding has occurred more frequently and severely. In response to the severe flooding, the Chinese government has created many policies and regulations to address the growing stormwater management concern. Beijing Municipal Government Order No. 66, issues on December 1, 2000, presents urban stormwater and flood management requirements for stormwater utilization and flood control. Additional stormwater management policies are summarized below:

- The Interim Regulation on Stormwater Resource Utilization with Physical Facilities implemented in March 2003
- Notice of Strengthening Water Saving Facility Management jointly issued by Beijing Planning Commission, Construction Commission, and Water Authority in December 2005
- Stormwater Utilization Proposal jointly issued by seven agencies including Beijing Water Authority in April 2006
- Notice of Strengthening Stormwater Utilization Facility of Construction Projects jointly issued by Beijing Water Authority, Development and Reform Commission, Planning Commission, Construction Commission, Transportation Commission, Forestation Administration, Land Bureau, and Environmental Protection Bureau in November 2006
- Technical Specifications for Stormwater Control and Utilization of New Physical Facilities promulgated by Beijing Planning Commission in August 2012

- Notice of Further Strengthening Construction of Urban Public Green Area with Stormwater Utilization issued in September 2012.

The introduction and application of international new concepts and technologies, including LID approaches, has led to a more integrated urban stormwater management approach in Beijing. This approach includes a series of engineering, technical, regulatory, and legal measures to address urban floods, frequent waterlogging, and nonpoint source pollution caused by large-scale urbanization. Beijing is the pioneer in urban stormwater utilization with three tested technical approaches, including land infiltration, collection and reuse, and controlled discharge (Vojinovic and Huang, 2014). In recent years, Beijing has started moving toward adopting multifunctional solutions using the LID approach. More specifically, the city currently features the largest application of pervious pavement. The Beijing Evaluation Standard for Green Buildings requires that pervious pavement should be at least 40% of the pavement surface outside public buildings. In 2011, the total area of pervious pavement in the city totaled 3.28 million square meters (Vojinovic and Huang, 2014). Other LID measures applied in Beijing include depressed green spaces, grass swales, rain gardens, bioretention cells, and stormwater ponds.

Plans to build a signature green building in downtown Beijing began as early as 1999 as an agreement between China’s Ministry of Science and Technology and the US Department of Energy. The 130,000 m^2 building was coordinated to demonstrate how a green building could dramatically reduce carbon emissions and environmental impacts. The building, which finished construction in 2004, was awarded a LEED gold rating in 2005. The building uses stormwater reuse to achieve its water demands and two years of data demonstrate savings of more than 40% in potable water use and a 60% reduction in wastewater generation. Moreover, 65% of the roof is covered by a roof garden with more than 80 species of native plants. Because the building uses local plant species in a roof garden and landscaping, accompanied by a stormwater collection and reuse system, it needs no potable water for irrigation, saving about 10,000 tons of potable water per year. The vegetated roof also serves as a comfortable retreat for occupants and greatly reduces the heat island effect. Integrative utilization of a roof garden, pervious pavement, native landscaping, and stormwater recycling not only significantly reduces runoff by 90%, but also mitigates the urban heat island effect, improving the local climate (Jin and Alyas, 2008).

2.3.4.2 Singapore

Singapore is a highly urbanized country with a population that has doubled since 1980, resulting in 5.5 million people total. Therefore, sustainable management of water resources is essential for the future development of Singapore. Singapore has been importing water from Malaysia. However, the first agreement expired in 2011 and the second will expire in 2061. The Government of Singapore has strong intentions to become self-sufficient in water supply by maximizing water yields and managing water quality at catchment scale. There are currently 16 surface water reservoirs which are partially inter-linked in Singapore. There are many operational challenges as each reservoir faces the trade-off between maximizing water storage and minimizing urban flood risk. In the future, Singapore aims to capture nearly all surface runoff from domestic and industrial areas. However, part of the rainfall is currently lost due to rapid runoff and reservoir system overload and therefore, has to be intermittently released to the sea. Additionally, due to an increase in impervious areas, infiltration that accounts for sub-surface flow and base flow is reduced significantly, resulting in strong ecological impacts due to reduced groundwater storage beneath the city.

To better manage its water resources, Public Utilities Board (PUB) of Singapore, launched the Active, Beautiful, Clean (ABC) Waters Program in 2006 (PUB, 2014). The program is based on a similar concept as LID, but with a focus on improving the quality of water and life. It targets to transform Singapore into a "City of Gardens and Water". The master plan includes more than 100 projects to be completed by 2030. The projects intend to create a vibrant (i.e., **A**ctive) and aesthetically pleasing (i.e., **B**eautiful) environment through features such as bioretention systems and constructed wetlands. The ABC Water design incorporates stormwater treatment on-site prior to discharging runoff into waterways, thus improving overall water quality (i.e., **C**lean). The vision is to improve water quality and to create new urban spaces and landscapes full of life, activity, and a sense of community around the waterbodies. It is also in line with recent interests in enhancing and restoring urban biodiversity in Singapore. The ABC Waters design features are developed based on the principles of reducing runoff and peak flow rates, improving water quality draining to receiving environments, integrating stormwater treatment into the landscape, recreational amenities, and protecting and enhancing natural water systems within developments (PUB, 2011)

In addition to the ABC elements implemented by PUB, greenroofs and porous pavement have been implemented in Singapore. Urban Redevelopment Authority (URA) and National Park Board (NParks) provide guidelines and encourage both public and private realms to install greenroofs through a series of initiatives. A number of extensive and intensive greenroofs have been installed (e.g., Parkway Parade, Suntec City, and Vivocity) and are expected to meet the Sustainable Development Blueprint target of an additional 50 hectares of skyrise greenery by 2030. However, the motivation behind greenroof installations in Singapore is mostly on energy savings and mitigating the urban heat island effect. There have been extensive studies in Singapore to confirm the thermal benefits of greenroofs to both buildings and their surrounding environments (e.g., Wong, et al, 2003). However, relatively fewer studies explore the contributions of greenroofs in stormwater management. Van Spengen (2010) recovered and stored rainwater on a 1 m^2 pilot-scale greenroof. He also performed catchment-scale hydrological simulations on the Sunset Way subcatchment in Singapore but found minimal reduction of peak flows due to limited building coverage in that particular subcatchment. The study of and implementation of porous pavement in Singapore is also limited. Fwa, et al. (2001) and Ong and Fwa (2005) evaluated and proposed designs of porous pavement for Singapore roads and car-parks. They developed approaches to examine the drainage properties and the thickness requirements of pavement materials, as well as the deterioration trends in permeability due to clogging, using both laboratory and numerical studies. Porous pavement has not been widely adopted in Singapore.

Pilot projects in Singapore have demonstrated that plant establishment and water quality, in terms of total suspended soils and nutrient concentrations, have been improved. While celebrating its success in achieving some of the ABC objectives, there is less emphasis in creating hydrologic controls using ABC Waters design features, partly because of the extreme urbanized city environment and the high capacity of the existing drainage system. On the other hand, there are concerns regarding mosquitos and dengue fever as a result of ponded water. Only recently has there been a growing interest in retaining and regulating runoff using ABC Waters design features. Additional clauses were added to the Code of practice on Surface Water Drainage in 2013, focusing on using ABC Waters Design features together with structural detention and retention features, to detain and treat stormwater runoff at the source (PUB, 2011). Industrial, commercial, institutional, and residential developments greater than or equal to 0.2 hectares in size are required to meet the maximum allowable peak runoff discharge calculated based on a runoff coefficient of 0.55 and design storms with a return period of 10 years for durations up to 4 hours (PUB, 2011).

The ABC Waters Program is led and driven by the government, setting an example to other relevant parties. However, the government has been promoting and encouraging the adoption of ABC Waters to the community using the 3P (People, Public, Private) partnership approach. The ABC Waters Design Guidelines were first promulgated in 2009 to encourage private and public sectors to implement ABC Waters design features and preserve waterways within their developments. ABC Waters projects and relevant activities are open to schools, grassroots organizations, and community groups. Resources have been put into developing ABC Waters design features that can be easily and widely installed. PUB also launched the recognition program ABC Waters Certification scheme in 2010 to recognize the efforts of public agencies and private developers that incorporate ABC Waters design features into their developments (PUB, 2016a). In return, the developments can be promoted as ABC Waters certified. In 2011, the ABC Waters Professional Program was established by the Institution of Engineers Singapore (IES), and supported by Singapore Institute of Architects (SIA), Singapore Institute of Landscape Architects (SILA) as well as PUB, National Park Boards, Housing and Development Board, and the Land Transport Authority (PUB, 2016b). It aims to nurture more experts in the concept, design, implementation, and maintenance of ABC Waters design features. Participants meeting the registration criteria of IES/ SIA/ SILA can be registered as an ABC Waters Professional by passing the examinations for all four core modules and two electives. ABC Waters Professionals are engaged in the design, construction supervision, and maintenance plan for any ABC Waters design feature.

2.3.4.3 Hong Kong

Hong Kong (HK), located on the southern coast of China, is a highly urbanized city with around 7 million people and a land area of about 1000 km^2. HK currently imports over 70% of its freshwater supply from East River, Guangdong Province, China. However, the East River also supplies water to seven rapidly developing major cities such as Guangzhou and Shenzhen, resulting in a strain on freshwater resources. Therefore, there is an incentive to harvest more rainwater as a secondary freshwater source in HK. On the other hand, stormwater has been managed relatively independently from other water supplies. HK has built extensive networks of conventional drains to efficiently divert stormwater away from urbanized areas into the sea. Together with traditional stormwater infrastructure, such as underground drainage tunnels and storage tanks, HK has successfully alleviated flooding in many flood-prone areas. Unfortunately, this process has degraded many river habitats, resulting in the loss of valuable water resources.

Most LID elements (i.e., bioretention swales, rain gardens, construction wetlands) are not commonly adopted in HK and are in experimental stages. There are ongoing discussions and a few actual installations but LID concepts are not widely known. Of the various types of LID, the most commonly used technique is greenroofs. Over 90 greenroof projects were completed in schools, office buildings, community facilities, and government quarters (Development Bureau, 2014). Incentive programs exist that encourage the design and construction of green and innovative buildings that can protect and improve the built and natural environment. For example, sky gardens and other green features can be exempted from gross floor area calculations under the Building Ordinance (Buildings Department, Lands Department and Planning Department, 2002). However, the incentives for greenroof installations are mostly for energy savings, urban heat island mitigation, and communal uses. The potential hydrologic benefits of greenroofs have not been recognized in HK. The second commonly adopted LID is porous pavement. Grass pavers and porous block pavers have been installed in some locations (Chan and Cheng, 2012). Highways Department recommends the use of porous asphalt for standard surfacing in expressways and high speed roads (Highways Department, 2007) to encourage water infiltration, improve skid resistance, and reduce water spray from vehicles. Highways Department has also collaborated with local universities to perform research on increasing the durability and cost effectiveness of porous asphalt (Highways Department, 2006). However, similar to greenroofs, the potential benefits in stormwater management are not yet recognized in HK.

As stated in the Policy Address of 2015 given by HK Chief Executive, the HK government would promote green building and energy conservation, as well as water-friendly culture and activities. The government would directly address pollution and odor nuisances caused by the discharge of urban pollutants into coastal waters (The Government of HKSAR, 2015). It would also adopt the concept of revitalizing waterbodies in large-scale drainage improvement works and planning drainage networks for new development areas (NDAs), so as to build a better environment for the public. LID could help address these issues, though it is not specified in the Policy Address. In other words, there are government initiatives and policies that are in line with LID techniques. However, there is not yet policy and regulation in guiding or requiring LID in HK. Example policies that are in line with LID include the greening policy of Planning Department which promotes greening in both public work projects and private sectors through planting, maintenance, and preservation of trees and vegetation (Planning Department, 2007). There are also specific requirements on open spaces for both landscaping and passive recreation use for different building types (i.e., residential, industrial and commercial). The current greening policy focuses highly on enhancing environmental quality as well as the quality of life for citizens. However, stormwater management is not considered one of the driving forces for creating urban green spaces.

In terms of the specific implementation of LID, the government has been and is expected to continue to play the leading role in HK. For example, in response to the Policy Address in 2015, Drainage Services Department (DSD) became even more active in revitalizing waterbodies in large-scale drainage improvement works and planning drainage works for NDAs. It has also utilized greenroofs in DSD facilities and has harvested rainwater at two of its sewage pumping stations in Kowloon City (DSD, 2013), and is planning to carry out more rainwater harvesting projects. Furthermore, DSD is exploring with a private company, Ove Arup & Partners, and The University of Hong Kong the construction of LID elements in Stonecutter Islands Sewage Treatment Work. Another government department, Civil Engineering and Development Department (CEDD) has been leading the incorporation of LID in NDAs, through implementation of greenroofs, bio-retention systems, porous pavements, and attenuation lakes. Finally, HK Housing Authority has been working with a private company, AECOM, to incorporate rainwater harvesting in housing development plans. A feasibility study was conducted and detailed design that included greenroofs, covered walkways, and planted slopes were produced (Wong, 2014).

Other than government departments, HK Green Building Council also launched a comprehensive building environmental assessment scheme called BEAM Plus (HKGBC, 2016) that is in line with LID. BEAM Plus gives credits and recognizes environmental practices that are above regulatory requirements. It considers six main aspects: site aspects, material aspects, energy use, water use, indoor environmental quality, and innovations and additions. It encourages runoff reduction and specifically recognizes greenroof systems that control both stormwater quantity and quality. It also requires landscaping and greenery to enhance living conditions and reduce hydrological impacts. It further encourages the use of pervious materials for hard-landscaped areas to reduce the consumption of energy and freshwater, and recognizes rainwater harvesting as a method for reducing freshwater consumption. LID is considered an innovative technique that is welcomed and could be credited after assessment.

The pilot government projects, use of LID techniques in NDAs, and the voluntary building assessment scheme are all effective starting points. However, in the long run, LID implementation should be more comprehensive, requiring close collaborations of government, construction industry, private developers, and environmental organizations. Therefore, integrated and comprehensive strategy and policy are required to ensure smooth implementation. This includes, but not limited to, promotion, incentives, education, and regulation. One possible approach is to incorporate LID policy into existing greening policy, pilot projects, incentives, and regulation. Formation of a LID steering committee, with members from all relevant sectors, would also facilitate implementation. Current examples of multi-sectoral collaborations are the value management workshops held by CEDD during project planning of NDAs. Various relevant government departments, academics, and professional organizations are invited to brainstorm innovative ideas and share their concerns. Multi-sectoral working groups are also set up throughout the projects to facilitate communication, develop consensus, address concerns, and resolve conflicts.

2.3.5 *LID Technology and Policy in Europe*

Various LID schemes have been proposed and implemented to differing degrees across Europe including the urban forest, green belt and green heart, green fingers or wedges, greenways, green infrastructure, ecological frameworks, and ecological networks (James et al., 2009). The European Biodiversity Strategy to 2020 includes a commitment from the European Commission to develop a widespread GI strategy. In Europe, GI is recognized as contributing to regional policy and sustainable growth, and facilitating smart and sustainable growth through smart specialization (European Commission, 2013). GI can make a significant contribution to the effective implementation of all policies where some or all of the desired objectives can be achieved in whole or in part through nature-based solutions. In Europe, there is usually a high return on GI investments and overall reviews of restoration projects typically show cost-benefit ratios in the range of 3 to 75 (European Commission, 2013). Over 60% of Europe's population lives in urban environments, making GI solutions of particular importance in terms of health, clean air, reducing the spread of vector-borne disease, and creating a sense of community.

The development of GI in Europe is currently at a crossroads. Over the last 20 years, numerous GI projects have been carried out and there is abundant evidence demonstrating that the approach is flexible, sound, and cost-effective. However, to optimize the functioning of GI and maximize its benefits, work on the different scales of GI should be interconnected and interdependent (European Commission, 2013). For the full potential of GI to be realized, the modalities for using it must be established to facilitate its integration into projects funded by the Common Agricultural Policy, the Cohesion Fund, the European Regional Developments Fund, Horizon 2020, the Connecting Europe Facility, the European Maritime and Fisheries Fund, and the Financial Instrument for the Environment. At the European level, Horizon 2020 and the European Regional Development Fund are potential sources of support for research on and innovation in GI (European Commission, 2013).

2.3.6 *Case Studies within Europe*

2.3.6.1 Germany

Engineered greenroofs originated in northern Europe, where sod roofs and walls have been used for hundreds of years. The development of contemporary approaches to greenroof technology began in the urban areas of Germany over 30 years ago (Buehler et al., 2011). The proliferation of greenroofs and other GI in Germany has been supported by a complex assortment of incentives and requirements at multiple levels of the government. Federal nature-protection laws and building codes require compensation, or restoration, for human impairment of natural landscapes. In many cases, GI techniques can be used to fulfill these requirements. Federal laws also require that German states create landscape plans, resulting in a variety of innovative approaches to environmental protection, many of which have involved elements that first incentivized and later required the creation and maintenance of GI (Buehler et al., 2011).

A series of German federal and state court rulings, beginning in the 1970s, have required increased transparency and equitable rate structures for stormwater services. The majority of German households are charged for stormwater services based on an estimate of the stormwater burden generated from their properties, known as an individual parcel assessment (IPA). Since IPAs in Germany are used to assess fees that directly relate to conditions present on specific parcels, land-use decisions such as permeable pavement or greenroofs have major impacts on the amount of stormwater leaving a property and create discounts for individuals who incorporate GI on their property (Buehler et al., 2011). Assessing each property's share of the stormwater burden effectively turns what is a diffuse, nonpoint pollution source into a point-source problem. IPAs also create economic incentives, such as the fee-and-subsidy system or emission trading, to encourage GI where it can cost-effectively manage stormwater (Buehler et al., 2011).

In summary, the success of GI in Germany can be attributed to four key concepts. Firstly, policies must start small and be implemented in stages. Many sustainability policies in Germany were first implemented at a small geographic scale and expanded in stages over time. Secondly, policies have to be coordinated and integrated across sectors and levels of government to achieve maximum effectiveness. Thirdly, communicate policies with citizens and foster citizen participation. Citizen input reduces potential legal challenges, increases public acceptance, and has the potential to grow projects and improve outcomes. Lastly, find innovative solutions and embrace bipartisanship. Successful green policies in Germany were designed to meet the needs of multiple constituents (Buehler et al., 2011). The remarkable development and success of GI in Germany was encouraged by state legislation and municipal government grants. Other European states and cities have adopted similar types of support and policy, with several mid to large-size cities incorporating roof and vertical greening into their bylaws and planning regulations (Magill et al., 2011).

2.3.6.2 United Kingdom

Development of green roof guidelines have been constructed based on academic research, product development, and field observations. These guidelines, known as the German Landscape Research, Development, and Construction Society, are often used for green roofs throughout

Europe and are recognized as the most respected guidelines on the subject (Magill et al., 2011). The first national green roof conference in the United Kingdom (UK) was held at the University of Sheffield in September 2003. This conference led to a working partnership between the University of Sheffield and the Sheffield City Council, and led directly to the implementation of green roof projects in the region. In 2009, Groundwork Sheffield and Green Roof Centre began work on a code of best practice for green roof design, specification, installation, and maintenance. At the time, there was no UK-specific guidelines or standards pertaining to green roofs. With assistance from major industry players, such as the National Federation of Roofing Contractors, the first Green Roof Code was published in February 2011.

As part of the approach to more sustainable living and climate change adaption, in addition to planning properly for community greenspace, GI is increasingly recognized as a "must have" which is reflected in various aspects of UK's national planning policy. National planning policy for England is principally contained with the National Planning Policy Framework (NPPF). The NPPF requires local planning authorities to use the term green infrastructure and defines it as "a network of multi-functional green space, urban and rural, which is capable of delivering a wide range of environmental and quality of life benefits for local communities" (RTPI, 2013). In the NPPF, the burden is on local planning authorities to develop strategic networks of GI and take account of the benefits of GI in reducing the risks posed by climate change. In 2005, Planning Policy Statement 1: Delivering Sustainable Development, stated that developments should ensure an appropriate mix of uses, including incorporation of green space. In 2007, this policy was expanded upon by stating that spatial strategies and any development should help deliver, amongst other things, GI and biodiversity as part of a strategy to address climate change mitigation and adaptation. In 2008, Planning Policy Statement 12: Local Spatial Planning, required local planning authorities to assess GI requirements and stated that core strategies should be supported by evidence of what physical, social, and GI is needed to enable the amount of development proposed for the area, taking account of its type and distribution (Natural England, 2009).

2.3.7 *Australia*

LID is referred to as water-sensitive urban design (WSUD) in Australia. The history of WSUD can be traced back to the early 1990s when the need for integrated water management became apparent. A motivating factor behind WSUD, given the arid climate of Australia, is the potential to harvest stormwater as a water resource. Currently, there is no national regulation for urban water management. However, different states have begun publishing WSUD guidelines. Federal, state, and territory governments created the National Water Initiative (NWI) in 2004 (National Water Commission, 2016). The NWI is a comprehensive national strategy to improve water management across the country, including the adoption of WSUD.

Policies and regulations vary among different state and local governments. Many promote and encourage sustainable development with only limited specific regulatory requirements for WSUD. In Victoria, WSUD is incorporated into the overall state planning and strategies. For example, a major objective of the Victoria Planning Provisions, prepared by the Victoria State Government, is mitigating the impact of stormwater on bays and catchments. There are limited strategies for achieving this objective which include mitigating stormwater pollution from construction sites and ensuring stormwater does not impact wetlands and estuaries. One strategy explicitly covers the incorporation of WSUD for developments to protect and enhance natural water systems, integrate stormwater treatment into the landscape, protect water quality, and reduce run-off and peak flow rates (Victoria State Government, 2016). Furthermore, new residential subdivisions of two or more lots are required to meet the integrated water management objectives including those for urban run-off management. For urban run-off management, other than meeting the requirements of the relevant drainage authority and water authority, urban stormwater management systems should be designed to meet the current best practice performance objectives for stormwater quality, outlined in the Urban Stormwater – Best Practice Environmental Management Guidelines (Victorian Stormwater Committee 1999). Systems are required to produce downstream flowrates equal to pre-development levels and ensure downstream impacts are mitigated.

2.3.8 *Sponge Cities*

For thousands of years, city planners have engineered water into submission, such as through the use of aqueducts. The core of modern water infrastructure is to collect water along the outskirts of the city, send it by gravity or pumps into the city, and then dispose of it underground in a sewer. Areas stricken by drought such as Los Angeles, California, waste precious rainwater when it slides off rooftops or flows over impermeable pavement and enters sewers. The Los Angeles River, which was transformed into a narrow concrete channel to control the risk of flooding in the 1940s, discharges precious rainwater into the port of Long Beach. In response to the severe California drought, city planners and engineers have decided to build Los Angeles as a "sponge." The idea of a sponge city is to soak up stormwater and treat it as a precious resource. Elmer Avenue, a working class neighborhood within Los Angeles, has spent $2.7 million to retrofit its streets with permeable pavement and drought-tolerant landscaping. Each of the sidewalks within Elmer Avenue contains a bioswale and when it rains, water collects and filters down through the bioswales into cisterns buried beneath the street. The city block collects enough water during an average rain year to provide water for 30 million families (Standen, 2015). Rooftops in Los Angeles are regarded as “mouths wide open to the sky” or “umbrellas turned upside down” to capture as much rain as possible. Furthermore, plumbing in Los Angeles should be smarter, meaning toilets should not be flushed with potable water, but instead, flushed with recycled stormwater (Standen, 2015).

In September 2015, the Chinese government approved the development of 16 model sponge cities, or ecologically friendly alternatives to the concrete intensive, gray urban expanses of modern China. This initiative requires infrastructure retrofits of existing cities all over China, ranging from Xixian New Area in the north (population of about 500,000), to Chongqing in the south (population of about 10 million). Each city will receive 400 million RMB ($63 million) per year for three years to implement projects. A sponge city is one that can hold, clean, and drain water in a natural way using an ecological approach, says Kongjian Yu, the dean of Peking University’s College of Architecture and Landscape Architecture. China began experimenting with sponge-related urban designs more than a decade ago. In 2000, one of the first large studies involving LID was used in the design of a housing block called Tianxu Garden in Beijing. During the Beijing flood of 2012, which killed 79 people, the apartments easily survived the disaster thanks to the LID technology and sponge characteristics (O’Meara, 2015). The Chinese government wants to change city models from gray to green; however, not many people know how to design a sponge city, which is expected to be the next frontier of LID and GI.

2.3.9 *Economic Aspects of Utilizing LID*

A common misconception regarding the use of LID practices is they cost more than conventional methods of stormwater management, or gray approaches. However, LID can actually cost less than conventional stormwater management and be environmentally beneficial. EPA recently commissioned a detailed study of 17 development projects that used LID techniques and compared the actual cost to the estimated cost of conventional stormwater management techniques. The study found that LID can achieve significant cost savings through reduced grading, landscaping, paving, and infrastructure costs (i.e. curbing, pipes, and catch basins) (USEPA, 2009). LID also has the potential to eliminate or reduce the size of required stormwater infrastructure by reducing the total volume of generated stormwater runoff, which provides more open space or buildable lots. Overall, total LID capital costs were lower than conventional methods, with savings ranging from 15 to 80 percent (USEPA, 2009). This information can be found in the EPA report titled *Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices*.

It is now evident that LID techniques can be implemented at or less than the cost of conventional stormwater management practices and offer many environmental services. An additional economic analysis of countries utilizing LID or GI techniques reveals a direct correlation between the use of LID and a country's gross domestic product (GDP). Analysis of the top 50 countries by GDP shows that 70% of the countries regularly utilize LID techniques and policy for stormwater management, shown in Table 2-3. The average GDP of countries in the top 50 that regularly utilize LID is \$1,771,578$\times 10^6$ (US dollars); however, the average GDP of countries in the top 50 that do not regularly utilize LID is \$692,249$\times 10^6$ (US dollars). This information was obtained from the World Bank (2014) report and is summarized in Figure 2-2. This analysis shows a direct correlation between a country's economic success and their ability to manage stormwater in an environmentally sensible manner. This could be attributed to the prevention of flooding, protection of environmental resources, and higher quality of life, which result in part from utilizing LID.

Table 2-3. Countries by stormwater management strategy (nominal GDP in millions of US dollars)

LID and/or GI		Conventional stormwater management	
Country	GDP	Country	GDP
United States	17,419,000	India	2,066,902
China	10,360,105	Russia	1,860,598
Japan	4,601,461	Mexico	1,282,720
Germany	3,852,556	Turkey	799,535
United Kingdom	2,941,886	Saudi Arabia	746,249
France	2,829,192	Nigeria	568,508
Brazil	2,346,118	Argentina	540,197
Italy	2,144,338	Venezuela	509,964
Canada	1,786,655	Iran	415,339
Australia	1,453,770	Colombia	377,740
South Korea	1,410,383	Egypt	286,538
Spain	1,404,307	Chile	258,062
Indonesia	888,538	Kazakhstan	231,876
Netherlands	869,508	Iraq	229,327
Switzerland	685,434	Algeria	210,183
Sweden	570,591		
Poland	548,003		
Belgium	533,383		
Norway	500,103		
Austria	436,344		
United Arab Emirates	401,647		
Thailand	373,804		
South Africa	349,817		
Denmark	341,952		
Malaysia	326,933		
Singapore	307,872		
Israel	304,226		
Hong Kong	290,896		
Philippines	284,582		
Finland	270,674		
Pakistan	246,876		
Ireland	245,921		
Greece	242,230		
Portugal	227,324		
Czech Republic	208,796		

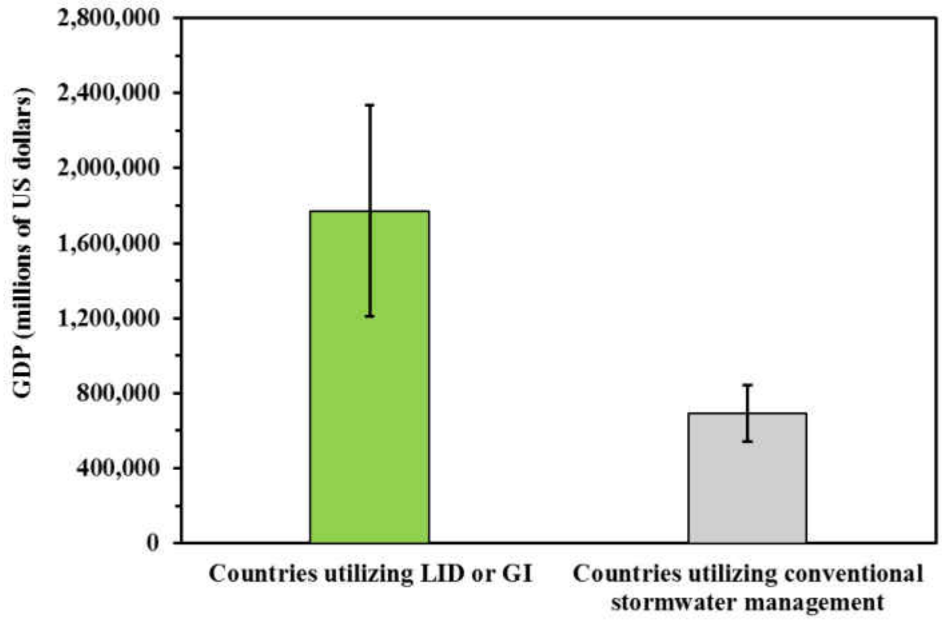

Figure 2-2. Comparison of GDP for countries by stormwater management technique

2.3.10 *Numeric Nutrient Criteria in the United States*

Numeric nutrient criteria (NNC) are a critical tool for protecting and restoring the designated uses of a waterbody with regard to nitrogen and phosphorus pollution. These criteria enable effective monitoring of a waterbody for attaining its designated uses, facilitate formulation of NPDES discharge permits, and simplify development of TMDLs for restoring waters not attaining their designated uses (USEPA, 2016). Currently, twenty-three states have issued some form of NNC in the US. A map of states with NNC guidelines is presented in Figure 2-3. Black circles in Figure 2-3 are used to pinpoint cities currently using a combined sewer system. There does not appear to be a strong correlation between the use of a combined sewer system and NNC; however, the majority of cities with a combined sewer system are found in the northeast, where many states have begun adopting some form of NNC. Moreover, many states in the Midwest have NNC, suggesting agricultural areas and the use of fertilizers may foster the creation of NNC, due to agricultural runoff and the degradation of receiving waterbodies. As seen in Figure 2-3, the majority of states have Level 2 NNC, meaning some waterbodies have nitrogen and/or phosphorus criteria. Only one state, Hawaii, currently has a complete set of nitrogen and phosphorus criteria for all waterbodies, known as Level 5 criteria.

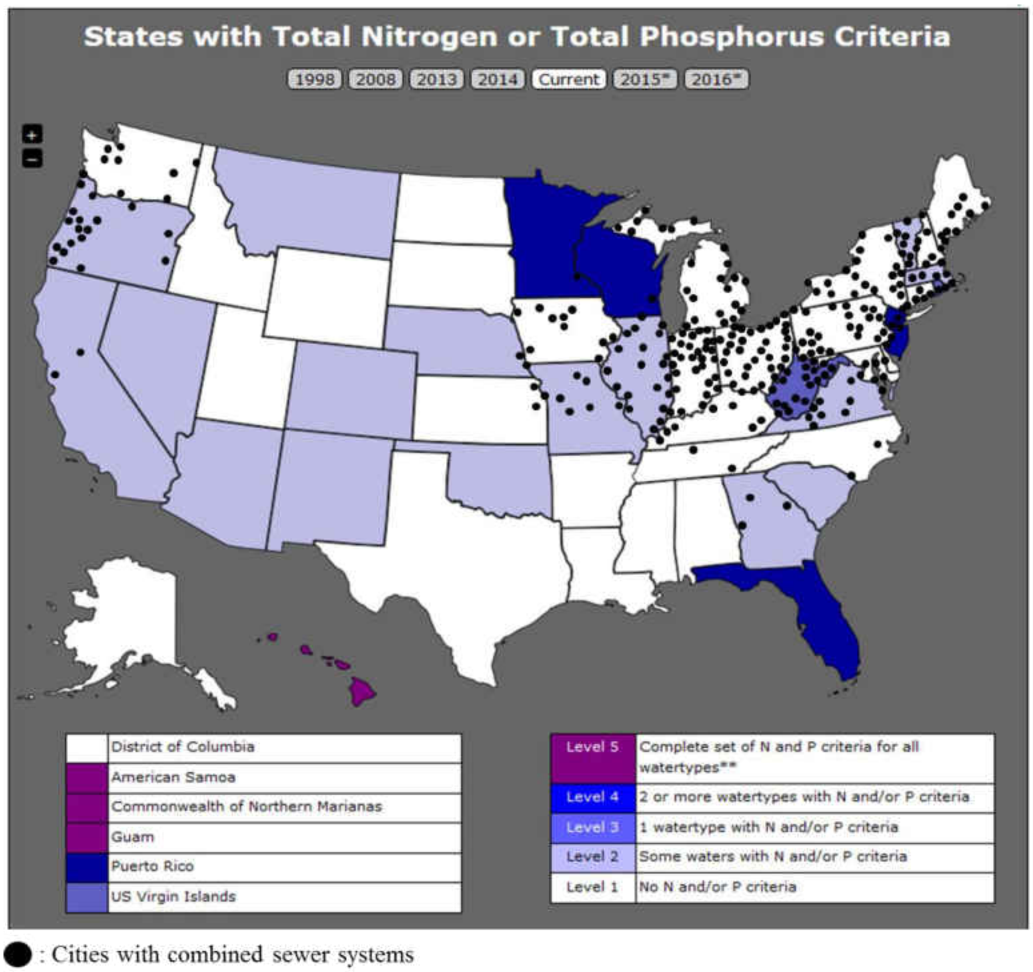

Figure 2-3. States currently utilizing numeric nutrient criteria (Source: EPA 2016)

Incorporation of LID or GI can help states meet NNC and stay in compliance with state and federal regulations. A major source of impairment for waterbodies across the US is when stormwater runoff introduces large quantities of nutrients, heavy metals, pathogens, and other pollutants to receiving waterbodies, following rainfall events. LID and GI can help reduce the total volume of stormwater runoff entering receiving waterbodies by capturing, infiltrating, storing, and treating stormwater at the source. Pollutants are removed through a combination of physical, chemical, and biological processes that occur through LID technology. For example, bioretention areas capture stormwater and utilize the water and nutrients to facilitate plant growth, additional pollutants may also be removed through infiltration. Incorporation of LID techniques in urban areas is a simple and cost-effective method for managing stormwater in a sustainable manner and may also contribute to states attaining their NNC and TMDLs.

2.3.11 *Incentives for LID*

As discussed in this chapter, there are many economic, social, and political incentives for utilizing LID in stormwater management. In areas that levy stormwater fees based on the stormwater burden generated by individual properties, the use of LID can reduce the quantity of generated stormwater and provide opportunities for citizens to receive fee discounts. LID can actually cost less than traditional methods of stormwater management, due to reduced grading, landscaping, paving, and infrastructure costs. LID can also eliminate or significantly reduce the size of required downstream stormwater infrastructure by reducing the total volume of generated stormwater. LID has been shown to create a sense of community by offering green spaces within urban areas for citizens to come together and reconnect with nature. Rain gardens, greenroofs, and other urban green spaces have been shown to have psychological benefits by reducing stress, restoring attention, and reducing criminal and anti-social behavior. LID techniques not only improve the hydrologic cycle in urban areas but also offers benefits in the areas of soil, ecology, air, and mitigating the urban heat island effect. LID offers the potential for multiple levels and sectors of government to work together to solve a common problem. Governments that communicate policies effectively with citizens and foster citizen participation have shown to be more successful. Moreover, successful green policies are created when governments embrace bipartisanship to meet the needs of multiple constituents.

2.3.12 *Lessons from International Experiences*

Many lessons can be taken away from studying LID policy in countries outside of the United States. For example, the fiscal support and encouragement of public participation in Germany could be translated to the successful implementation of LID in the US. Over the last 40 years, Germany has retooled policies to promote growth that is environmentally sustainable (Buehler et al., 2011). Germany's experiences can provide useful lessons for policy makers in the US and encourage the shift to sustainable urban developments and economy. Currently, most municipalities in the US lack the overlapping, reinforcing incentives and requirements that have led to the successful implementation of LID in Germany. IPAs offer the potential to provide funding for water-management authorities and encourage public participation through the implementation of LID techniques on private property. However, a major obstacle to this is the low rate currently charged for stormwater management in the US. It may prove difficult for stormwater facilities to charge fees high enough where incentives for on-site stormwater management would prove beneficial (Buehler et al., 2011).

2.4 Final Remarks

This chapter has shown there are a wide variety of approaches taken when implementing LID and GI in urban environments. Governments that take proactive and aggressive measures, whether through policies, regulations, or incentives, prove to be the most successful and are facilitating the shift from gray cities to green cities. Discounts on stormwater fees have proven to be an effective measure for encouraging public participation and provides incentives for homeowners to implement LID, such as greenroofs or permeable driveways, on their own property. Furthermore, stormwater should be regarded as a precious commodity as we move forward, not as a nuisance to be disposed of. Stormwater reuse can help meet the growing global water demand and LID is a valuable technique for securing and prolonging many freshwater resources. Moreover, the advantages of LID and GI extend past their ability to manage stormwater, as they also provide societal, economic, political, and aesthetic benefits. In conclusion, the policy of governments should be to encourage and support the development of green cities through the use of LID and discourage further environmental degradation by continuing the practice of constructing gray cities.

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CHAPTER 3: EFFECT OF FLOATING TREATMENT WETLANDS ON THE CONTROL OF NUTRIENTS IN THREE STORMWATER WET DETENTION PONDS

3.1 Introduction

Expansion of urban developments and agricultural production continues to result in nutrient-laden stormwater runoff that can have serious impacts on aquatic ecosystems and human health (Anderson et al., 2002). Stormwater wet detention ponds are a common best management practice (BMP) for treating stormwater runoff. Stormwater wet detention ponds are designed to hold a permanent pool of water that provides many beneficial uses. These benefits include flood mitigation, pollution prevention, downstream erosion control, increased aesthetics, and recreational uses. At times, nutrient inputs may exceed the treatment capacity of stormwater wet detention ponds, resulting in eutrophication of receiving waterbodies, harmful algal blooms (HABs), and deterioration of ecosystems.

Nutrients, such as nitrogen and phosphorus, are an essential component for maintaining a healthy aquatic environment; however, when these nutrients are in excess they begin to have adverse effects. Nitrogen and phosphorus-containing substances are found in urban stormwater runoff primarily from highways, residential areas, and grasslands in urban regions. Nitrates result from both vehicular exhaust on the road itself and from the use of fertilizers on the adjacent soils for landscaped areas. Elevated nitrate (NO_3-N) concentrations in drinking water has caused infant mortality from the disease methemoglobinemia (blue baby syndrome) and has toxic effects on livestock (Hubbard, 2010). Nitrate levels greater than 10 parts per million, the public health standard, have been documented in groundwater associated with agricultural activities in New

York, Wisconsin, Nebraska, Arkansas, Ontario, England, Georgia, and Oklahoma (Hubbard, 2010). Because nitrogen is frequently a limiting nutrient for plants, increased quantities of nitrogen in stormwater wet detention ponds can alter the competitive relationships among terrestrial and aquatic organisms.

Phosphorus is of environmental concern because elevated concentrations can lead to eutrophication, the dense growth of plant and algal species in surface waterbodies. In general, phosphate (PO_4-P) is considered to be of concern primarily for surface runoff since it binds to iron, aluminum, or calcium in the soil, depending on pH, and is not readily leachable (Hubbard, 2010). On the basis of diffusion studies, Olsen and Watanabe (1970) concluded that there was an eight times greater risk of PO_4-P pollution of groundwater in sandy soils than in clayey soils, making phosphate a pollutant of concern in Florida. Over fertilization leading to nutrient-laden runoff can accelerate the eutrophication process, resulting in aquatic environments becoming hypereutrophic. This process can result in dissolved oxygen levels falling below 2 $mg \cdot L^{-1}$, which can suffocate aquatic organisms and cause serious impacts on aquatic ecosystems and human health (Chang et al., 2012). If sufficient nutrient reduction is not provided by the stormwater wet detention pond, this buildup of excess nutrients can result in the collapse of an aquatic ecosystem or influence toxin-producing algal species (Anderson et al., 2002).

An innovative and newly emerging BMP for assisting in nutrient reduction in stormwater wet detention ponds is the installation of floating treatment wetlands (FTWs). FTWs are a manmade ecosystem that mimics natural wetlands (Sample et al., 2013). Plants grow on interlocking, floating foam mats, rather than at the bottom of the pond, which enables them to interact with suspended nutrients in the water column. FTWs support the growth of root systems of the floating plants, which offers a large surface area in the root zone for microbial nutrient removal processes (Govindarajan, 2008) and entrapment of suspended particles (Headley and Tanner, 2006). Pollutant reduction occurs through three primary mechanisms: 1) Plants directly uptake nutrients from the water using a process known as biological uptake; 2) microorganisms growing on the floating mats and plant root systems break down and consume organic matter in the water through microbial decomposition; and 3) root systems filter out sediment and associated pollutants (Sample et al., 2013). The choice of macrophyte species to plant on the floating mats often comes down to selecting locally present native species that exhibit vigorous growth within polluted waters under the local climate conditions (Headley and Tanner, 2006). FTWs offer an environmentally sustainable and economical approach for nutrient reduction in stormwater wet detention ponds. The cost of FTWs can range from $1 (homemade, recycled, or PVC products) to $24 (commercial and proprietary mats) per square foot.

Wetlands can be classified into four main categories: 1) free water surface (FWS) wetlands, 2) horizontal subsurface flow (HSSF) wetlands, 3) vertical flow (VF) wetlands, and 4) free-floating plants (FFP) wetlands (Vymazal, 2007). In this study, FTWs are considered a variation of the typical FFP wetlands, where instead of plants freely floating on the water surface they are concentrated in specific areas and placed on floating mats. While most natural floating vegetation found in FFP wetlands is at or slightly above the water surface, use of a floating platform to support the plants allows for growth of relatively large plants (Hubbard, 2010). Tall vegetation can produce considerable amounts of biomass which corresponds to significant nutrient reduction in the waterbody (Hubbard, 2010). Most constructed wetland systems have permanent vegetation which means that plant tissue ultimately falls to the bottom of the wetland as it senesces. These wetland systems do not provide removal of nutrients, only cycling from the water to sediment. Use of FTWs allows for easier removal of biomass during maintenance; therefore, nutrients taken up by plants are ultimately removed from the waterbody (Hubbard, 2010). A summary of the different wetland types, average nutrient reduction efficiencies, advantages, and limitations is presented in Table 3-1.

Table 3-1. Types of wetlands

Type of Wetland	Description	Average Reduction Efficiencies	Advantages	Limitations	References
Free water surface (FWS)	▪ Areas of open water, floating vegetation, and emergent plants, similar in appearance to natural marshes.	TN: 41% TP: 49%	▪ Attract a wide variety of wildlife ▪ Cost-competitive ▪ Suitable for a wide variety of climates	▪ Require large land areas	Vymazal (2006) Kadlec (2009) Kadlec and Wallace (2009)
Horizontal subsurface flow (HSSF)	▪ Employ a gravel or soil bed planted with wetland vegetation. ▪ Water, kept below the surface of the bed, flows horizontally from inlet to outlet.	TN: 42% TP: 41%	▪ Risk of exposure to pathogenic organisms is minimized because water is not exposed during treatment ▪ Ability to operate in cold climates because of insulation effect	▪ More expensive than FWS ▪ Cannot handle large flow rates due to cost and space considerations ▪ Propensity for clogging of the media	Vymazal (2006) Kadlec (2009) Kadlec and Wallace (2009)
Vertical flow (VF)	▪ Distribute water across the surface of a sand or gravel bed planted with wetland vegetation. ▪ Water is treated as it percolates through the plant root zone.	TN: 45% TP: 60%	▪ Provide higher levels of oxygen transfer compared to HSSF ▪ Ability to oxidize ammonia ▪ Can treat very concentrated wastewaters	▪ Propensity for clogging of the media ▪ More expensive than FWS ▪ Can't handle flow rates similar to FWS wetlands	Vymazal (2006) Kadlec (2009) Kadlec and Wallace (2009)
Floating treatment wetland (FTW)	▪ Plants, placed on floating mats, remove nutrients and other pollutants through a combination of nutrient uptake and microbial decomposition.	TN: 55% TP: 42%	▪ Flexible design that can be sized to fit many waterbodies ▪ Enhances pollutant reduction in existing stormwater wet ponds ▪ Provides a sustainable pollutant reduction system and wildlife habitat ▪ Can tolerate water level fluctuations resulting from storm events	▪ Anchoring of floating matts can be a challenge ▪ Plant replacements can be labor intensive ▪ Invasive species can invade, creating unwanted competition and harming the local ecosystem ▪ Pond depth should be greater than length of roots	Vymazal (2006) Kadlec (2009) Kadlec and Wallace (2009) Sample and Fox (2013) White and Cousins (2013)

The comparative evaluation of nutrient reduction is aimed at answering the following science questions: 1) Does the inclusion of FTWs improve nutrient reduction in stormwater wet detention ponds? 2) Are the three real world ponds (Gainesville, Ruskin, and Orlando) able to be compared based on initial nutrient concentrations? 3) If the initial conditions are similar, is there a significant difference in the level of nutrient reduction with the inclusion of FTWs at the three stormwater wet detention ponds?

3.1.1 *Chapter Objectives*

The objective of this chapter is to assess the nutrient reduction capacity of three stormwater wet detention ponds containing FTWs and perform a statistical analysis on reduction effectiveness using data collected from the ponds. Rigorous sampling of water quality at Orlando, Gainesville, and Ruskin allowed for a non-parametric test to assess and compare nutrient reduction rates across the three ponds systematically. The contribution of this chapter is to provide scientific evidence for the effectiveness of a novel, environmentally sustainable BMP in stormwater management.

3.2 Methodology

For consistency and ease of reference throughout this chapter the following terminology will be used to describe the sampling time periods. 1) Phase 1: The pre-analysis sampling time period before installation of the FTWs. 2) Phase 2: The post-BMP sampling time period after installation of the FTWs. 3) Phase 3: The post-plant-replacement sampling time period after replacing plants on the FTWs. The significance of collecting water quality samples during these three phases is that it provides information on the stormwater wet detention pond's performance before and after installation of the FTWs. Samples were collected during Phase 1 in order to assess the baseline performance of the stormwater wet detention pond without inclusion of FTWs. Samples were collected during Phase 2 and Phase 3 to assess the pond's performance after installation of the FTWs and after plant replacement on the FTWs, respectively. Sampling of the stormwater wet detention ponds was accomplished by taking water quality samples at the inlet and outlet of each pond. Three non-storm samples were taken during Phase 1 for each pond. Three non-storm and three storm samples were taken during Phase 2 for each pond. Five non-storm samples were taken during Phase 3 for each pond. Storm samples are defined in this study as water quality samples collected from the stormwater wet detention ponds during or directly following (within a few hours) rainfall events. Storm samples were collected following storm events with total rainfall quantities equal to or greater than 0.25 inches. Non-storm samples are defined in this study as water quality samples collected from the stormwater wet detention ponds during the inter-event dry period, the period of time between storm events. The inter-event dry period must be sufficiently long so that two rainfall events are independent of one another.

3.2.1 *Gainesville Pond*

The Gainesville pond has an area of 2,363 m^2 and is located in Gainesville, Florida at the low point between two hills to the east and west. The pond receives runoff from State Road 26 which is located directly to the south. The pond is flanked by a forest to the east and north and a residential area located to the west. Overland flow from the surrounding forest and residential area flows directly into the pond, as well as runoff pooling at the low point of State Road 26 which is discharged into the pond through stormwater piping. The experimental design for this pond was divided into three phases: Phase 1 (January 2014 – February 2014), Phase 2 (February 2014 – July 2014), and Phase 3 (December 2014 – April 2015). This pond suffered from severe algal growth that covered the entirety of the pond surface, as well as floating debris which entered through the stormwater piping system.

This pond utilized three buoyant, foam mats provided by Beemats, LLC. The interlocking puzzle-cut design of each mat enables the floating mats to be assembled in various sizes and shapes. Nylon connectors were stapled onto adjacent mats in order to provide stability for the whole FTW system. The FTWs deployed in this pond covered roughly 5% of the pond's surface area. A complete replacement of the FTW plants was performed on November 5, 2014. The FTWs installed in the Gainesville pond are presented in Figure 3-1. The plants selected for placement in pre-cut holes on the mats for this pond were Canna, Juncus, Blue Flag Iris, and Agrostis.

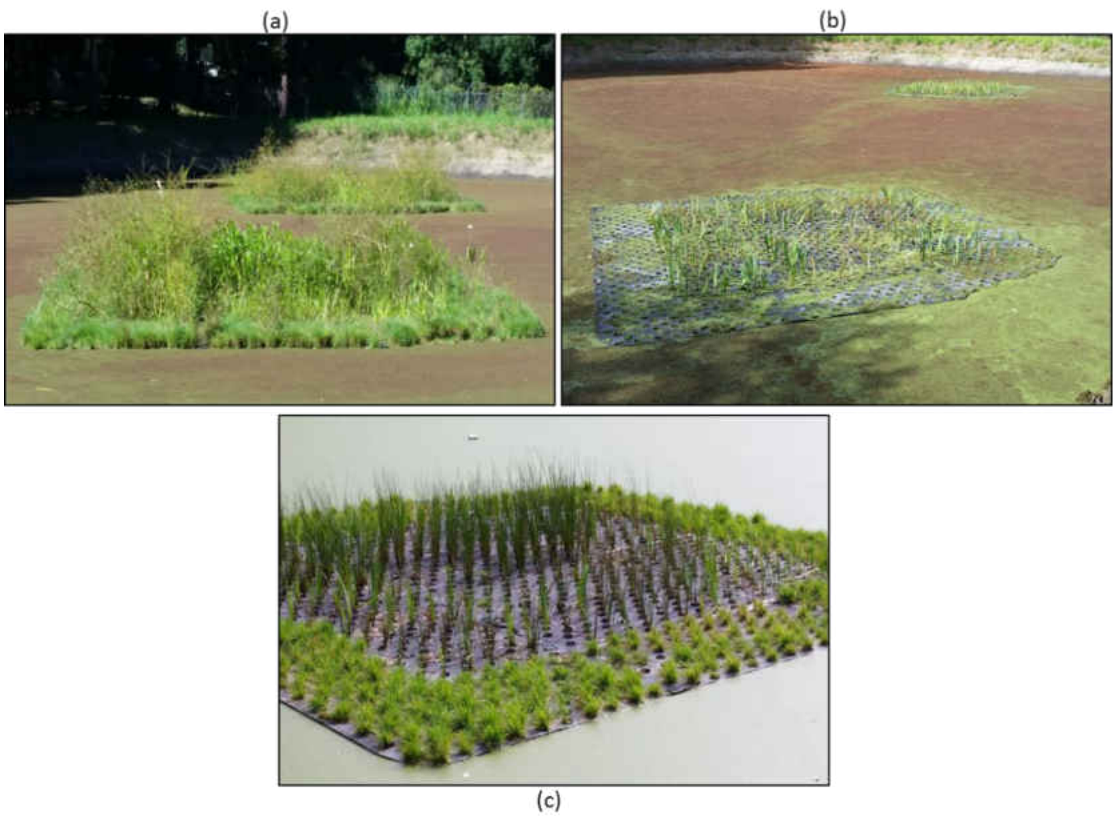

Figure 3-1. FTWs at Gainesville Pond, (a) seven months after installation, (b) after plant replacement, and (c) four months after plant replacement

3.2.2 *Ruskin Pond*

The Ruskin pond has an area of 1,263 m^2 and is located in Ruskin, Florida, adjacent to a tomato field to the south and west, a commercial shopping area to the east, and a residential neighborhood to the north. This stormwater wet detention pond was constructed in 1994. The pond has excessive vegetative growth in the littoral zone, which could be explained by a high influx of nutrients from the adjacent tomato field. Similar to the Gainesville pond, there was severe algal growth that covered the entirety of the pond surface. The experimental design period for this pond was divided into three phases as follows: Phase 1 (December 2013 – January 2014), Phase 2 (February 2014 – May 2014), and Phase 3 (October 2014 – March 2015).

The Ruskin pond utilized a buoyant, foam mat provided by Beemats, LLC. Due to the thick vegetative growth around and within the pond and a smaller pond size, only one FTW was installed. A complete replacement of the FTW plants was performed on September 17, 2014. The FTW deployed in this pond covered roughly 5% of the pond's surface area. The FTW installed in the Ruskin pond is presented in Figure 3-2. The plants selected for placement in pre-cut holes on the mats for this pond were Canna, Juncus, Blue Flag Iris, and Agrostis.

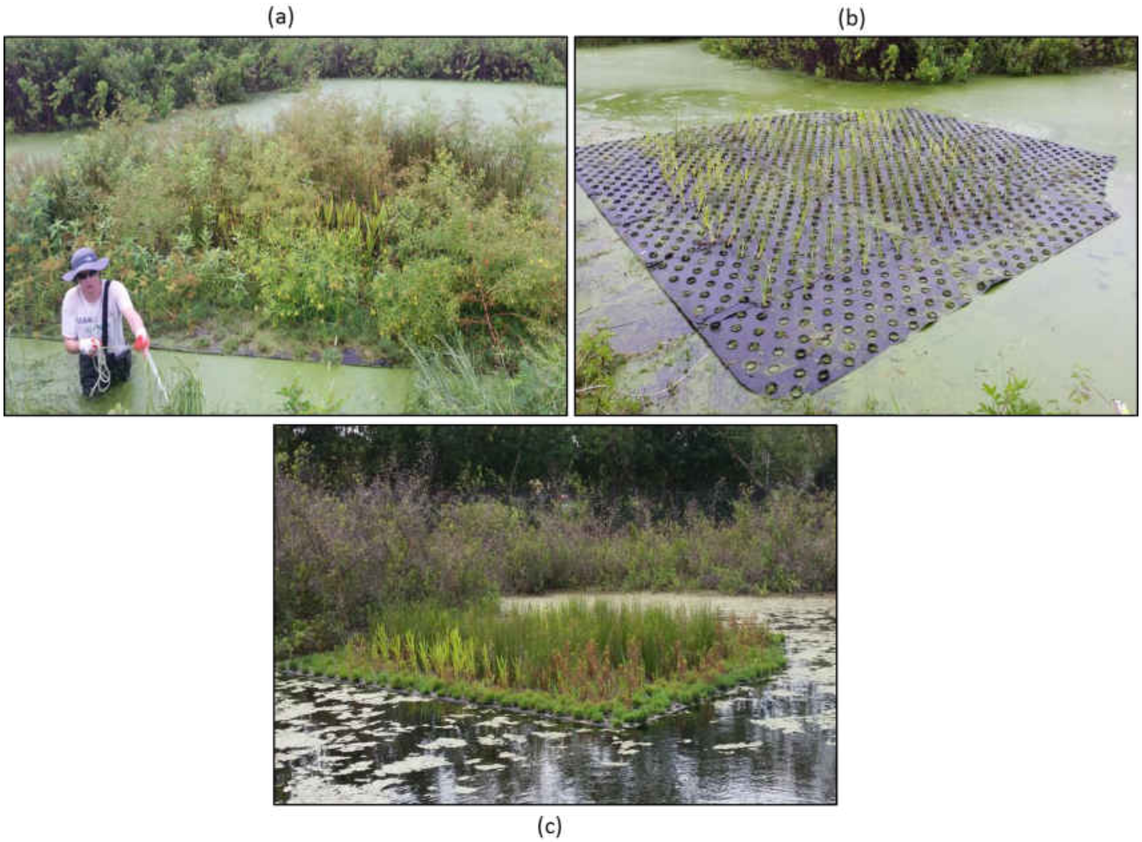

Figure 3-2. FTW at Ruskin Pond, (a) eight months after installation, (b) after plant replacement, and (c) six months after plant replacement

3.2.3 *Orlando Pond*

The Orlando pond, called Pond 4M locally, is a stormwater wet detention pond located in Orlando, Florida. The pond was constructed in 2000. The land use surrounding the pond is classified as low density commercial, primarily composed of roadways, offices, and small shopping centers on the main campus of The University of Central Florida. The pond receives stormwater runoff from areas with cars parked for extended periods of time but relatively low traffic volumes. The pond surface area is 2,792 m^2 and is directly surrounded by woods, grassy areas, and commercial buildings. The experimental design period was divided into three phases:

Phase 1 (November 2010 – April 2011), Phase 2 (April 2011 – December 2011), and Phase 3 (December 2011– April 2012).

Pond 4M utilized three buoyant, foam mats provided by Beemats, LLC to evenly distribute the plants throughout the pond. The plants selected to be placed in pre-cut holes were Canna, Juncus, and Agrostis. The FTWs were deployed on April 8, 2011, and covered roughly 6.4% of the pond surface area, which has been proven a cost-efficient coverage rate for FTWs in similar environmental conditions (Chang et al., 2012). The FTWs installed in Pond 4M are presented in Figure 3-3.

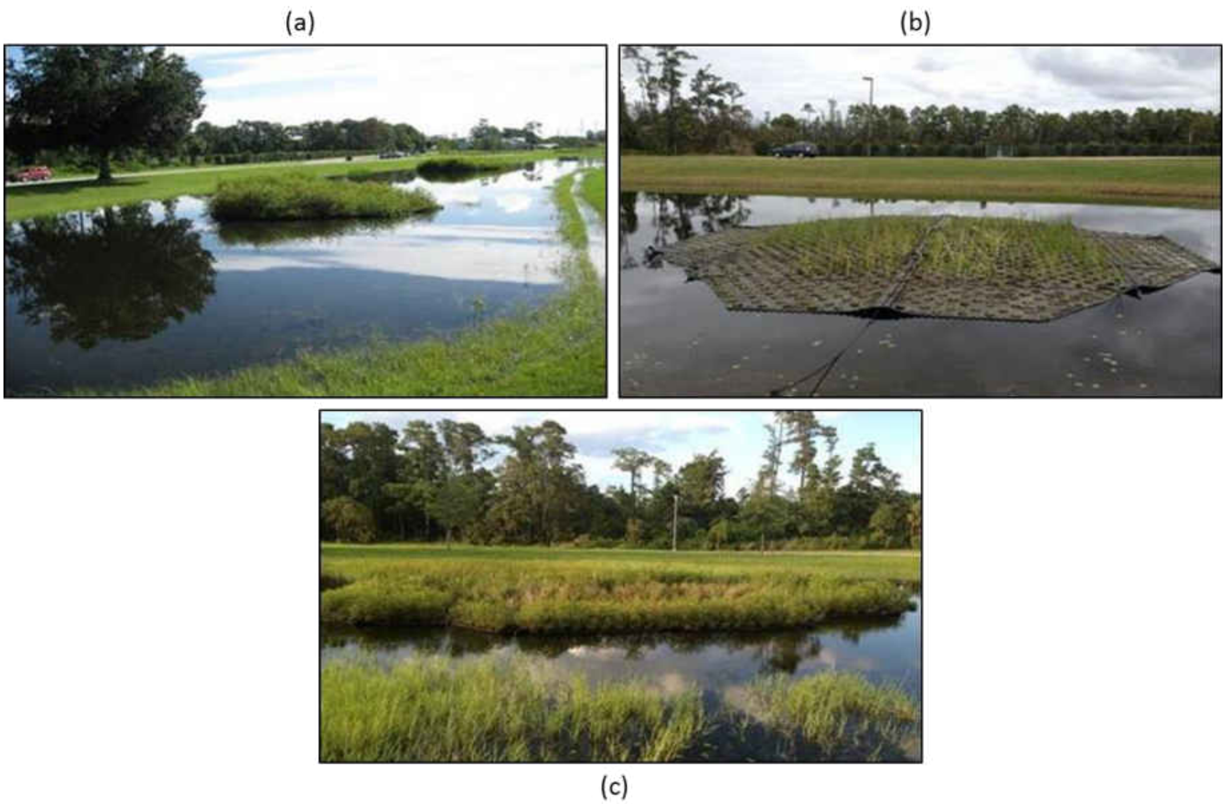

Figure 3-3. FTWs at Pond 4M in Orlando, (a) six months after installation, (b) after plant replacement, and (c) five months after plant replacement

3.2.4 *Comparison of the Three Ponds*

The three stormwater wet detention ponds are all located in Florida; however, some of their characteristics are different. Table 3-2 presents a comparison of the key parameters related to stormwater management for each stormwater wet detention pond. Beemat FTW products were utilized in each of the three ponds. The Orlando pond is the newest of the three stormwater wet detention ponds, having been constructed in 2000. The surface area of the Gainesville and Orlando ponds are relatively similar; however, the Ruskin pond is roughly half the size of the other two ponds. Ruskin having a smaller surface area could result in lower hydraulic residence times and a smaller permanent pool volume, depending on depth. The FTW coverage percentage for each of the three ponds is very similar with all values falling in the range of five to seven percent. The watershed characteristics of the three ponds are also similar, with the majority of the surroundings being classified as roadways, residential, or grassy areas. The shape of the Gainesville and Ruskin ponds are similar; however, the shape of the Orlando pond is quite unique. The Orlando pond utilizes a long, rectangular shape design while the other two ponds are closer to a square in design.

Table 3-2. Wet Detention Pond Characteristics

Characteristics	Gainesville	Ruskin	Orlando
FTW Type	Beemat	Beemat	Beemat
Construction Year	1992	1994	2000
Location	Gainesville, FL.	Ruskin, FL.	Orlando, FL.
Surface Area (m^2)	2,363	1,263	2,792
Surroundings	▪ Highway ▪ Woods ▪ Residential	▪ Highway ▪ Commercial ▪ Tomato field	▪ Commercial ▪ Woods ▪ Grassy areas
Pollution Sources	▪ Vehicular exhaust ▪ Fertilizers ▪ Plant litter	▪ Fertilizers ▪ Vehicular exhaust ▪ Pesticides	▪ Vehicular exhaust ▪ Vehicle wear and tear ▪ Fertilizers ▪ Organic debris
FTW Coverage Rate	5.0%	5.0%	6.4%
Pond Shape	Rectangular	Rectangular	Rectangular and Long

3.2.5 *Nutrient Evaluation*

Water quality samples were collected at five locations from the inlet to outlet pipes in the Orlando pond. For the Gainesville and Ruskin ponds, water quality samples were collected at the locations of the inlet and outlet pipes. In order to measure the effectiveness of nutrient reduction with inclusion of FTWs, nutrient percentage reductions were calculated in Phase 1, Phase 2, and Phase 3 of the project. All samples were transported at 4ºC to a National Environmental Laboratory Accreditation Program (NELAP) certified laboratory called Environmental Research & Design (ERD), located in Orlando, Florida, for nutrient analysis. The percent reduction of nutrients was calculated using the water quality data collected for each of the three ponds. The following equation was utilized:

$$CRP = \frac{C_{inflow} - C_{outflow}}{C_{inflow}} * 100\% \quad (3\text{-}1)$$

where CRP = concentration reduction percentage (%), C_{inflow} = influent concentration ($mg \cdot L^{-1}$), and $C_{outflow}$ = effluent concentration ($mg \cdot L^{-1}$).

Total organic nitrogen concentrations were evaluated using Standard Method: 4500-N(Org) C. Semi-Micro-Kjeldahl. The Kjeldahl method 4500-N(Org) C determines nitrogen in the tri-negative state. It fails to account for nitrogen in the form of azide, azine, azo, hydrazone, nitrate, nitrite, nitrile, nitro, nitroso, oxime, and semi-carbazone. Kjeldahl nitrogen is the sum of organic nitrogen and ammonia nitrogen. In the presence of sulfuric acid (H_2SO_4), potassium sulfate (K_2SO_4), and cupric sulfate ($CuSO_4$) catalyst, amino nitrogen of many organic materials is converted to ammonium. Free ammonia is also converted to ammonium. After addition of base, the ammonia is distilled from an alkaline medium and absorbed in boric or sulfuric acid. The ammonia may be determined colorimetrically, by ammonia-selective electrode, or by titration with a standard mineral acid (Standard Methods, 2011). Total nitrogen can be calculated by simply summing total Kjeldahl nitrogen (ammonia, organic, and reduced nitrogen) and nitrate-nitrite nitrogen (NO_x).

Total phosphorus concentrations were evaluated using Standard Method: 4500-P F. Automated Ascorbic Acid Reduction Method. Orthophosphates can be determined in potable, surface, and saline waters over a range of 0.001 to 10.0 mg $P \cdot L^{-1}$ when photometric measurements are made at 650 to 660 or 880 nm in a 15-mm or 50-mm tubular flow cell, respectively. Although the automated test is designed for orthophosphate only, other phosphorus compounds can be converted to this reactive form by various sample pretreatments described in Section 4500-P.B.

Ammonium molybdate and potassium antimonyl tartrate react with orthophosphate in an acid medium to form an antimony-phosphomolybdate complex, which, on reduction with ascorbic acid, yields an intense blue color suitable for photometric measurement (Standard Methods, 2011).

3.2.6 *Hypotheses and Statistical Analysis*

The hypotheses to be tested in this chapter are as follows. 1) There is no significant difference in initial influent concentrations of total nitrogen (TN) and total phosphorus (TP) across the Orlando, Gainesville, and Ruskin ponds. 2) There is no significant difference between influent and effluent TN and TP concentrations with the inclusion of a FTW compared to before installation of a FTW during storm or non-storm events. 3) There is no significant difference in percent reduction of TN and TP between Phase 1 and Phase 2 conditions. 4) There is no significant difference between influent and effluent TN and TP concentrations or percent reductions after plant replacement during Phase 3. The significance of selecting these hypotheses is that the statistical analysis and testing of the hypotheses will provide crucial insight into the nutrient reduction potential of FTWs. The testing of these hypotheses is aimed at determining if implementation of FTWs into existing stormwater wet detention ponds is an effective BMP for enhancing nutrient reduction rates. Hypothesis 1 is important because it tests whether or not the ponds can be combined into a single data set, based on influent nutrient concentrations. If influent nutrient concentrations are not significantly different from one another, the three ponds can be combined into a single data set, which will increase the power of the statistical model by increasing the size of the tested data set.

The statistical analysis performed in this paper involves the use of the statistics software JMP Pro, Version 11 for analysis of nutrient reduction in the three stormwater wet detention ponds and evaluation of significant differences (JMP®, 2012). ANOVA and ANCOVA models may be used to compare the nutrient reduction in the three ponds, as they can accommodate the three levels of the treatment when combining all three ponds. In the event that the data does not meet the distribution assumptions required for parametric tests, a non-parametric test, Kruskal-Wallis, will be substituted. The confidence interval (CI) of 90% ($\alpha < 0.10$), highly significant for $p < 0.0001$ and non-significant for $p > 0.1000$ will be used for all tests.

3.3 Results and Discussion

3.3.1 *Ruskin Pond*

The water quality sampling and percent reduction results for the Ruskin stormwater wet detention pond during Phase 1 and Phase 2 sampling periods are presented in Table 3-3 and Table 3-4, respectively. Water quality samples were taken at the pond's inlet and outlet structures. The reduction efficiency was calculated using the concentration reduction percentage equation (equation 3-1). Values within the brackets represent the lower and upper bounds for the average reduction rate at the 90% confidence interval.

Table 3-3. Ruskin nutrient data and percent reductions in Phase 1

Nutrient	Event Type	Date	Inlet ($mg \cdot L^{-1}$)	Outlet ($mg \cdot L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Non-Storm	12/23/13	0.165	1.018	-517.0	-146.1 [-455.1, 162.9]
		01/14/14	0.146	0.165	-13.0	
		01/28/14	0.868	0.072	91.7	
TN	Non-Storm	12/23/13	0.682	3.259	-377.9	-95.3 [-329.4, 138.8]
		01/14/14	0.636	0.533	16.2	
		01/28/14	1.482	0.360	75.7	

Table 3-4. Ruskin nutrient data and percent reductions in Phase 2

Nutrient	Event Type	Date	Inlet ($mg·L^{-1}$)	Outlet ($mg·L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Storm	02/12/14	0.144	0.108	25.0	-35.9 [-99.8, 25.0]
		04/08/14	0.090	0.117	-30.0	
		09/02/14	0.109	0.221	-102.8	
	Non-Storm	05/05/14	0.120	0.190	-58.3	-119.1 [-275.6, 37.4]
		06/09/14	0.136	0.127	6.6	
		06/18/14	0.053	0.215	-305.7	
TN	Storm	02/12/14	0.567	0.289	49.0	33.1 [-25.2, 91.4]
		04/08/14	0.612	0.824	-34.6	
		09/02/14	1.480	0.223	84.9	
	Non-Storm	05/05/14	0.810	0.800	1.2	-25.5 [-53.6, 2.6]
		06/09/14	0.507	0.611	-20.5	
		06/18/14	0.422	0.664	-57.3	

3.3.2 *Gainesville Pond*

The water quality sampling and percent reduction results for the Gainesville stormwater wet detention pond during Phase 1 and Phase 2 sampling periods are presented in Table 3-5 and Table 3-6, respectively. Water quality samples were taken at the pond's inlet and outlet structures. The reduction efficiency was calculated using the concentration reduction percentage equation (equation 3-1). Values within the brackets represent the lower and upper bounds for the average reduction rate at the 90% confidence interval.

Table 3-5. Gainesville nutrient data and percent reductions in Phase 1

Nutrient	Event Type	Date	Inlet ($mg \cdot L^{-1}$)	Outlet ($mg \cdot L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Non-Storm	01/16/14	0.549	0.373	32.1	-3.1 [-33.5, 27.3]
		01/21/14	0.299	0.331	-10.7	
		02/04/14	0.236	0.308	-30.5	
TN	Non-Storm	01/16/14	0.678	0.268	60.5	-23.7 [-139.7, 92.3]
		01/21/14	0.352	0.239	32.1	
		02/04/14	0.196	0.517	-163.8	

Table 3-6. Gainesville nutrient data and percent reductions in Phase 2

Nutrient	Event Type	Date	Inlet ($mg \cdot L^{-1}$)	Outlet ($mg \cdot L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Storm	02/26/14	1.105	0.263	76.2	71.2 [67.0, 75.4]
		03/17/14	0.777	0.249	68.0	
		07/15/14	0.998	0.305	69.4	
	Non-Storm	04/16/14	0.294	0.288	2.0	36.2 [6.9, 65.5]
		05/14/14	0.510	0.192	62.4	
		06/24/14	0.388	0.217	44.1	
TN	Storm	02/26/14	0.831	0.335	59.7	36.5 [12.5, 60.5]
		03/17/14	0.570	0.340	40.4	
		07/15/14	0.676	0.612	9.5	
	Non-Storm	04/16/14	0.426	0.620	-45.5	-93.8 [-135.0, -52.9]
		05/14/14	0.379	0.870	-129.6	
		06/24/14	0.376	0.776	-106.4	

3.3.3 *Orlando Pond*

The water quality sampling and percent reduction results for the Orlando stormwater wet detention pond during Phase 1 and Phase 2 sampling periods are presented in Table 3-7 and Table 3-8, respectively. Water quality samples were taken at five points from the inlet to the outlet; however, only the inlet and outlet concentrations for the Orlando pond were utilized for analysis.

The reduction efficiency was calculated using the concentration reduction percentage equation (equation 3-1). Values within the brackets represent the lower and upper bounds for the average reduction rate at the 90% confidence interval.

Table 3-7. Orlando nutrient data and percent reductions in Phase 1

Nutrient	Event Type	Date	Inlet ($mg \cdot L^{-1}$)	Outlet ($mg \cdot L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Non-Storm	12/12/10	0.015	0.012	20.0	-43.5 [-127.9, 40.9]
		01/13/11	0.056	0.059	-5.4	
		02/15/11	0.040	0.098	-145.0	
TN	Non-Storm	12/12/10	0.586	0.611	-4.3	2.8 [-5.7, 11.3]
		01/13/11	1.023	1.024	-0.1	
		02/15/11	0.965	0.842	12.7	

Table 3-8. Orlando nutrient data and percent reductions in Phase 2

Nutrient	Event Type	Date	Inlet ($mg \cdot L^{-1}$)	Outlet ($mg \cdot L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Storm	06/24/11	0.020	0.020	0.0	-28.6 [-59.9, 2.7]
		10/08/11	0.017	0.028	-64.7	
		10/31/11	0.019	0.023	-21.1	
	Non-Storm	07/17/11	0.037	0.033	10.8	22.4 [-5.9, 50.7]
		08/16/11	0.014	0.014	0.0	
		09/15/11	0.016	0.007	56.3	
TN	Storm	06/24/11	0.840	0.840	0.0	4.2 [0.4, 8.0]
		10/08/11	0.383	0.365	4.7	
		10/31/11	0.375	0.345	8.0	
	Non-Storm	07/17/11	0.613	0.208	66.1	17.2 [-24.3, 58.7]
		08/16/11	0.480	0.461	4.0	
		09/15/11	0.328	0.388	-18.3	

3.3.4 Statistical Analysis

After performing the statistical distribution tests which test for normality and equal variance, required for parametric models, it was evident that the majority of the data did not meet the assumption requirements, typical of environmental data. Therefore, a non-parametric model, utilizing the Wilcoxon and Kruskal-Wallis tests, was used to perform the statistical analyses. The normality assumption is not required for non-parametric models and they are often used as an alternative to parametric models when the underlying linear assumptions cannot be met. The chi-square (χ^2) metric uses a p-value similar to ANOVA p-values. Chi-square values above the critical value ($P > \chi^2$) for the appropriate degrees of freedom (df = 1 in this study), supports the probability of finding a statistical difference at a CI of 90% ($\alpha < 0.10$). The one-way tests all have df = 1 for two groups (FTWs and control treatments or storm and non-storm conditions), and chi square test statistic (χ^2) values above the critical value of 2.706 are considered significant.

Testing the first hypothesis required checking for significant differences among inlet concentrations of TN and TP across the three ponds. Results showed no significant difference among TN inlet concentrations for the three ponds. However, the results did reveal a significant difference among TP inlet concentrations for the three ponds ($\chi^2 = 21.0$). This result is due to a large discrepancy between the Gainesville and Orlando TP inlet concentrations. The Orlando TP inlet concentrations were much lower compared to the Gainesville pond. This discrepancy may be explained by the surroundings and runoff characteristics of the Gainesville pond. In other words, the Gainesville pond may have elevated TP concentrations in stormwater runoff due to vehicle operation, application of fertilizers, and nutrients carried in from the forest floor. Moreover, TP levels in the Orlando pond may be naturally lower than the other ponds. Results from testing for significant differences among inlet concentrations are presented in Table 3-9. The TN inlet concentrations are not significantly different in this case because the test is analyzing three parameters, which is known as a Kruskal-Wallis test. For three parameters, the chi squared test statistic is no longer considered significant at a value of 2.706.

Table 3-9. Statistical analysis of inlet concentrations

Inlet Nutrient	Phase 1 and Phase 2	Sig. Difference	Hypothesis 1
TN Inlet Concentrations	$\chi 2 = 3.28 \rightarrow P>\chi 2 = 0.194$	NO	TRUE
TP Inlet Concentrations	$\chi 2 = 21.0 \rightarrow P>\chi 2 = 0.001$	YES	FALSE

Since each pond only has between 6-12 samples, a combined dataset utilizing data from all three ponds would increase the statistical power of the model and assist in correctly identifying significant differences. Due to the significant difference among TP inlet concentrations, the three ponds will not be combined into one dataset for analysis of TP reduction. The three ponds will be combined into one dataset for the analysis of TN reduction. The goal of the statistical analysis is to determine if there are significant differences between inlet and outlet concentrations of TN and TP for each pond and the combined data set. The statistical analysis will also test for differences in TN and TP percent reduction for each pond and the combined data set, between Phase 1, Phase 2, and Phase 3 conditions. The following sections provide a discussion of the results of the event-based statistical analysis for FTW nutrient reduction in the three ponds.

3.3.5 *Storm Based Statistical Analysis for Phase 1 and Phase 2*

The first statistical analysis for effectiveness of FTWs was focused on nutrient reduction capacity during storm events for Phase 1 and Phase 2 conditions across the three ponds. The following sections detail the storm based statistical analysis, which tests for significant differences among inlet and outlet concentrations of TN and TP, as well as significant differences among TN and TP percent reduction. A summary of the results found when testing for significant differences among inlet and outlet concentrations of TN and TP during storm events is presented in Table 3-10. A summary of the results found when testing for significant differences among TN and TP percent reduction from Phase 1 to Phase 2 during storm events is presented in Table 3-11.

Table 3-10. Statistical analysis of inlet and outlet concentrations for storm samples

Pond	Phase	Nutrient	$\chi 2$	$P>\chi 2$	Sig. Difference	Hypothesis 2
Ruskin	Phase 1	TN	0.429	0.513	NO	TRUE
		TP	0.000	1.000	NO	TRUE
	Phase 2	TN	1.190	0.275	NO	TRUE
		TP	0.429	0.513	NO	TRUE
Gainesville	Phase 1	TN	0.048	0.827	NO	TRUE
		TP	0.429	0.513	NO	TRUE
	Phase 2	TN	2.330	0.127	NO	TRUE
		TP	3.860	0.050	YES	FALSE
Orlando	Phase 1	TN	0.048	0.827	NO	TRUE
		TP	0.429	0.513	NO	TRUE
	Phase 2	TN	0.784	0.376	NO	TRUE
		TP	0.196	0.658	NO	TRUE
Combined Data	Phase 1	TN	0.329	0.566	NO	TRUE
	Phase 2	TN	3.960	0.047	YES	FALSE

Table 3-11. Statistical analysis of percent reduction for storm samples between Phase 1 and 2

Pond	Analysis	Nutrient	$\chi2$	$P>\chi2$	Sig. Difference	Hypothesis 3
Ruskin	Percent Reduction	TN	0.429	0.513	NO	TRUE
		TP	0.048	0.827	NO	TRUE
Gainesville	Percent Reduction	TN	0.048	0.827	NO	TRUE
		TP	3.860	0.050	YES	FALSE
Orlando	Percent Reduction	TN	0.429	0.513	NO	TRUE
		TP	0.048	0.827	NO	TRUE
Combined Data	Percent Reduction	TN	0.439	0.508	NO	TRUE

3.3.5.1 Ruskin Pond

There was no significant difference between inlet and outlet concentrations of TN and TP at the Ruskin pond for Phase 1 or Phase 2 conditions during storm events. Although reduction rates of TN improved during Phase 2, it could not be classified as significantly different. There was no significant difference in TN or TP percent reduction at the Ruskin pond for Phase 1 against Phase 2 conditions. Although the average reduction rate of TN increased from -95% during Phase 1 to 33% during Phase 2, due to the variability of the data, it could not be classified as significantly different.

3.3.5.2 Gainesville Pond

For the Gainesville pond there was no significant difference between inlet and outlet concentrations of TN and TP for Phase 1 conditions. However, during Phase 2 there was a significant difference among inlet and outlet concentrations of TP (χ^2 = 3.86). This suggests the FTWs were significantly effective at the Gainesville pond for enhancing TP reduction during storm events. The three storm samples taken from the Gainesville pond all saw elevated influent TP concentrations, averaging near a concentration of 1.0 mg·L^{-1}. However, the outlet TP concentrations for the storm samples had an average value of about 0.25 mg·L^{-1}. FTWs enhanced the reduction of TP and resulted in a TP reduction efficiency of over 70%, which is far superior to the -3% documented in Phase 1. Despite the TN reduction efficiency seeing an increase from -24% during Phase 1 to 37% in Phase 2, there was no significant difference in TN percent reduction at the Gainesville pond. There was a significant difference in TP percent reduction at the Gainesville pond for Phase 1 against Phase 2 conditions, which can be explained by the substantial increase in TP reduction demonstrated during Phase 2 storm conditions.

3.3.5.3 Orlando Pond

There was no significant difference between inlet and outlet concentrations of TP and TN at Pond 4M for Phase 1 or Phase 2 conditions. TP reduction saw a slight improvement at Pond 4M during storm conditions, with the TP reduction rate increasing from -44% during Phase 1 to -29% during Phase 2. Due to already low concentrations of TP at Pond 4M, improving reduction rates of TP was not considered as vital as enhancing TN reduction. The average inlet concentration of TP at Pond 4M during storm events was 0.019 mg·L^{-1}, while at Gainesville it was almost 1.0 mg·L^{-1}. Due to the naturally occurring low levels of TP at Pond 4M, even the slightest spike in phosphorus can result in reduction rates appearing worse than they are in reality. Although the reduction capacity for TP remained negative, the average outlet concentration was only 0.024 mg·L^{-1}. Reduction of TN remained relatively constant during storm events from Phase 1 to Phase 2 conditions. There was no significant difference in TN or TP percent reduction at Pond 4M for Phase 1 against Phase 2 conditions.

3.3.5.4 Combined Data Set

For the combined data set there was a significant difference among inlet and outlet concentrations of TN for Phase 2 storm conditions ($\chi^2 = 4.31$). This result reveals TN reduction, when viewed from a holistic perspective including all three ponds, was significantly enhanced with the inclusion of FTWs during Phase 2 storm events. There was no significant difference in TN percent reduction for the combined data set for Phase 1 against Phase 2 conditions. As previously stated, TP was not studied for the combined data set due to the large variability in TP inlet concentrations across the three ponds.

3.3.6 *Non-Storm Based Statistical Analysis for Phase 1 and Phase 2*

The second statistical analysis for effectiveness of FTWs focused on nutrient reduction during non-storm events for Phase 1 and Phase 2 conditions. The following sections detail the non-storm based statistical analysis for the three ponds, which tests for significant differences among inlet and outlet concentrations of TN and TP, as well as significant differences among TN and TP percent reduction between Phase 1 and Phase 2. A summary of the results found when testing for significant differences among inlet and outlet concentrations of TN and TP during non-storm events is presented in Table 3-12. A summary of the results found when testing for significant differences among TN and TP percent reduction from Phase 1 to Phase 2 is presented in Table 3-13.

Table 3-12. Statistical analysis of inlet and outlet concentrations for non-storm samples

Pond	Phase	Nutrient	χ2	P>χ2	Sig. Difference	Hypothesis 2
Ruskin	Phase 1	TN	0.429	0.513	NO	TRUE
		TP	0.000	1.000	NO	TRUE
	Phase 2	TN	0.429	0.513	NO	TRUE
		TP	2.330	0.127	NO	TRUE
Gainesville	Phase 1	TN	0.048	0.827	NO	TRUE
		TP	0.429	0.513	NO	TRUE
	Phase 2	TN	3.860	0.050	YES[1]	FALSE
		TP	3.860	0.050	YES	FALSE
Orlando	Phase 1	TN	0.048	0.827	NO	TRUE
		TP	0.429	0.513	NO	TRUE
	Phase 2	TN	1.190	0.275	NO	TRUE
		TP	0.784	0.376	NO	TRUE
Combined Data	Phase 1	TN	0.329	0.566	NO	TRUE
	Phase 2	TN	1.870	0.171	NO	TRUE

[1]Significant increase in outlet TN concentrations

Table 3-13. Statistical analysis of percent reduction for non-storm samples between Phase 1 and 2

Pond	Analysis	Nutrient	χ2	P>χ2	Sig. Difference	Hypothesis 3
Ruskin	Percent Reduction	TN	0.429	0.513	NO	TRUE
		TP	0.048	0.827	NO	TRUE
Gainesville	Percent Reduction	TN	0.429	0.513	NO	TRUE
		TP	2.330	0.127	NO	TRUE
Orlando	Percent Reduction	TN	0.048	0.827	NO	TRUE
		TP	1.190	0.275	NO	TRUE
Combined Data	Percent Reduction	TN	1.220	0.270	NO	TRUE

3.3.6.1 Ruskin Pond

There was no significant difference between inlet and outlet concentrations of TN and TP at the Ruskin pond for Phase 1 or Phase 2 conditions during non-storm events. TP reduction rates increased from -146% during Phase 1 to -119% during Phase 2. TN reduction rates increased from

-95% during Phase 1 to -26% during Phase 2. There was no significant difference in TN or TP percent reduction at the Ruskin pond for Phase 1 against Phase 2 conditions. Although reduction efficiencies of TN and TP both saw improvements, due to the variability of the data and the fact that sufficient reduction capacities were not achieved, the results cannot be classified as significantly different.

3.3.6.2 Gainesville Pond

For the Gainesville pond, there was no significant difference between inlet and outlet concentrations of TN and TP during Phase 1 non-storm conditions. There was a significant difference between inlet and outlet concentrations of TP for Phase 2 non-storm conditions (χ^2 = 3.86). The final two storm samples collected at Gainesville saw elevated influent TP concentrations when compared to the other sampling events. Despite these elevated TP concentrations, the outlet concentrations were actually lower than other sampling events, specifically outlet concentrations observed during Phase 1. This suggests the FTWs were significantly effective at enhancing TP reduction during both storm and non-storm conditions. There was no significant difference in TN reduction at the Gainesville pond for Phase 2 non-storm conditions. TN reduction at the Gainesville pond actually decreased during Phase 2 conditions, which is an interesting phenomenon not observed at the other ponds. The final two non-storm samples collected at Gainesville saw substantial spikes in TN outlet concentrations. One theory to explain these results is increased nitrogen loading from the residential and wooded areas located near the outlet, either as a result of fertilizer application or leaf litter entering the pond near the outlet. There was no significant difference in TN or TP percent reduction at the Gainesville pond for Phase 1 against Phase 2 conditions.

3.3.6.3 Orlando Pond

Pond 4M experienced increases in the nutrient reduction capacity of TN and TP for non-storm conditions during Phase 2. The reduction of TP increased from -44% in Phase 1 to 22% in Phase 2 for non-storm events. The reduction of TN increased from 3% in Phase 1 to 17% in Phase 2 for non-storm events. Despite these nutrient reduction improvements, there was not a significant difference between inlet and outlet concentrations of TN and TP during non-storm events. Also, there was no significant difference in TN or TP percent reduction at Pond 4M for Phase 1 against Phase 2 conditions. No significant differences among inlet and outlet concentrations and percent reduction can be explained by the variability of the data, most notably in the case of TN reduction.

3.3.6.4 Combined Data Set

For the combined data set, there was no significant difference between inlet and outlet concentrations of TN during Phase 1 or Phase 2 non-storm events. There was no significant difference in TN percent reduction for the combined data set for Phase 1 against Phase 2 conditions. Although the data cannot be classified as significantly different, it is evident that the FTWs played a vital role in enhancing TN reduction within the stormwater wet detention ponds during Phase 2 non-storm conditions, specifically at the Ruskin and Orlando sites.

3.3.7 *Non-Storm Based Statistical Analysis for Phase 3*

Plant replacements were performed at the Ruskin, Gainesville, and Orlando sites to characterize the nutrient reduction efficiency after mature plants had been removed and replaced with seedlings. Periodic maintenance of FTWs ensures mature plants do not die and reintroduce nutrients to the water column. As an extension to this study, an additional five non-storm samples were collected at each stormwater wet detention pond following plant replacement on the FTWs. The water quality sampling results for the Ruskin, Gainesville, and Orlando stormwater wet detention ponds are presented in Tables 3-14, 3-15, and 3-16, respectively. All water quality samples during Phase 3 were collected during non-storm events. Reduction efficiency of TP and TN improved at the Ruskin stormwater wet detention pond from Phase 2 to Phase 3. The average reduction efficiency of TP during non-storm events improved from -119% during Phase 2 to -17.2% during Phase 3. The average reduction efficiency of TN during non-storm events improved from -25.5% during Phase 2 to -6.2% during Phase 3.

Table 3-14. Ruskin nutrient data and percent reductions in Phase 3

Nutrient	Event Type	Date	Inlet ($mg \cdot L^{-1}$)	Outlet ($mg \cdot L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Non-Storm	10/07/14	0.099	0.199	-101.0	-17.2 [-65.6, 31.2]
		10/28/14	0.137	0.127	7.3	
		03/07/15	0.088	0.093	-5.7	
		03/16/15	0.068	0.074	-8.8	
		03/23/15	0.086	0.067	22.1	
TN	Non-Storm	10/07/14	0.648	0.448	30.9	-6.2 [-35.0, 22.6]
		10/28/14	0.731	0.868	-18.7	
		03/07/15	0.469	0.673	-43.5	
		03/16/15	0.477	0.535	-12.2	
		03/23/15	0.585	0.511	12.6	

Table 3-15. Gainesville nutrient data and percent reductions in Phase 3

Nutrient	Event Type	Date	Inlet ($mg \cdot L^{-1}$)	Outlet ($mg \cdot L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Non-Storm	12/21/14	0.492	2.727	-454.3	-59.4 [-284.5, 165.6]
		02/11/15	0.959	0.228	76.2	
		02/21/15	0.159	0.171	-7.5	
		04/18/15	4.271	4.319	-1.1	
		04/22/15	1.448	0.151	89.6	
TN	Non-Storm	12/21/14	3.497	5.072	-45.0	16.4 [-26.6, 59.3]
		02/11/15	1.503	0.562	62.6	
		02/21/15	0.456	0.396	13.2	
		04/18/15	9.432	9.427	0.1	
		04/22/15	1.298	0.636	51.0	

Table 3-16. Orlando nutrient data and percent reductions in Phase 3

Nutrient	Event Type	Date	Inlet ($mg \cdot L^{-1}$)	Outlet ($mg \cdot L^{-1}$)	Reduction (%)	Avg. Reduction (%)
TP	Non-Storm	12/16/11	0.012	0.015	-25.0	-33.1 [-48.5, -17.8]
		01/18/12	0.014	0.016	-14.3	
		02/14/12	0.008	0.011	-37.5	
		03/19/12	0.009	0.014	-55.6	
		04/18/12	0.009	0.012	-33.3	
TN	Non-Storm	12/16/11	0.444	0.434	2.3	-2.0 [-15.8, 11.7]
		01/18/12	0.512	0.513	-0.2	
		02/14/12	0.525	0.455	13.3	
		03/19/12	0.226	0.281	-24.3	
		04/18/12	0.249	0.252	-1.2	

An interesting phenomenon occurred at the Gainesville pond from Phase 2 to Phase 3. Reduction efficiency of TP decreased during Phase 3; however, the reduction efficiency of TN improved drastically. The average reduction efficiency of TP during non-storm events decreased from 36.2% during Phase 2 to -59.4% during Phase 3. The average reduction efficiency of TN during non-storm events improved from -93.8% during Phase 2 to 16.4% during Phase 3. A substantial improvement in the stormwater wet detention pond's capacity to reduce nitrogen was observed during Phase 3. The decrease in the reduction efficiency of phosphorus can be explained by one observation. The sampling event on December 21, 2014, saw a drastic spike in the effluent concentration of TP. The effluent TP concentration measured 2.73 $mg \cdot L^{-1}$, prior to this sample TP concentrations have generally been less than 1.0 $mg \cdot L^{-1}$ at the Gainesville pond. If this anomaly is excluded from the dataset, the average reduction efficiency of TP increases to 39.3% during Phase 3, which appears to be a more accurate continuation of performance when compared to the 36.2% documented during Phase 2. It should also be noted that the Gainesville pond experienced a wide range of TN concentrations with values ranging from 0.46 to 9.43 $mg \cdot L^{-1}$ at the inlet. Because the samples were collected during non-storm events, this wide range should not be expected, suggesting storm-events that occurred in the days prior to sampling or the surrounding land use practices may have caused elevated nitrogen concentrations in the pond.

Average reduction efficiencies of TP and TN both experienced a relapse during Phase 3 at the Orlando stormwater wet detention pond. The average reduction efficiency of TP during non-storm events decreased from 22.4% during Phase 2 to -33.1% during Phase 3. The average reduction efficiency of TN during non-storm events decreased from 17.2% during Phase 2 to -2.0% during Phase 3. The results for the reduction efficiency of TP at the Orlando site are misleading due to extremely low levels of phosphorus within the stormwater wet detention pond. The largest effluent concentration of TP at the Orlando site during Phase 3 was 0.016 $mg \cdot L^{-1}$, which presents no concern for nutrient impairment in terms of phosphorus concentrations. However, the decline in TN reduction efficiency is concerning, as elevated nitrogen concentrations can lead to the formation of HABs and disrupt ecosystem integrity. Further analysis of influent and effluent concentrations of TN at the Orlando site show minimal changes from inlet to outlet, suggesting an increased FTW coverage rate or repositioning of the FTWs to better intercept the stormwater flow may be beneficial.

A summary of the results found when testing for significant differences among inlet and outlet concentrations of TN and TP during non-storm events in Phase 3 is presented in Table 3-17. No significant differences among inlet and outlet nutrient concentrations were discovered during Phase 3. Comparison of average reduction efficiencies from Phase 2 to Phase 3 revealed one significant finding, presented in Table 3-18. The average reduction efficiency of TN at the Gainesville site significantly improved from Phase 2 to Phase 3 ($\chi^2 = 5.0$). Also, average reduction efficiency of TN for the holistic assessment of the three ponds greatly improved and was on the cusp of being classified as statistically significant ($\chi^2 = 3.34$). There was a significant decrease in TP percent reduction at the Orlando pond; however, as previously discussed, the low levels of phosphorus within the pond led to some misleading statistical outputs. Overall, the results from Phase 3 are promising and show continued improvements in the nutrient reduction capacity of the Ruskin and Gainesville ponds. Results from the Orlando site suggest accommodations should be made to improve nitrogen reduction, such as increasing the FTW coverage rate or repositioning the FTWs.

Table 3-17. Statistical analysis of inlet and outlet concentrations for non-storm samples in Phase 3

Pond	Phase	Nutrient	$\chi 2$	$P>\chi 2$	Sig. Difference	Hypothesis 4
Ruskin	Phase 3	TN	0.011	0.917	NO	TRUE
		TP	0.011	0.917	NO	TRUE
Gainesville	Phase 3	TN	0.750	0.387	NO	TRUE
		TP	0.333	0.564	NO	TRUE
Orlando	Phase 3	TN	0.011	0.917	NO	TRUE
		TP	3.211	0.073	NO	TRUE
Combined Data	Phase 3	TN	0.228	0.633	NO	TRUE

Table 3-18. Statistical analysis of percent reduction for non-storm samples between Phase 2 and 3

Pond	Analysis	Nutrient	$\chi 2$	$P>\chi 2$	Sig. Difference	Hypothesis 4
Ruskin	Percent Reduction	TN	1.089	0.297	NO	TRUE
		TP	1.089	0.297	NO	TRUE
Gainesville	Percent Reduction	TN	5.000	0.025	YES	FALSE
		TP	0.000	1.000	NO	TRUE
Orlando	Percent Reduction	TN	0.556	0.456	NO	TRUE
		TP	5.000	0.025	YES[1]	FALSE
Combined Data	Percent Reduction	TN	3.340	0.067	NO	TRUE

[1]Significant decrease in TP percent reduction from Phase 2 to Phase 3

3.3.8 *Nutrient Credits Acquisition*

Point source nitrogen and phosphorus credits can be defined as the difference between waste load allocations for a permitted facility, specified as annual mass load of TN or TP, and the monitored annual mass load of TN or TP discharged by that facility. For this case the facility would be a stormwater wet detention pond and the delivery factor would be expressed as pounds per year of nitrogen or phosphorus (Baxter, 2012). When FTWs are designed and maintained according to standards, a credit is recommended for their use. These nitrogen and phosphorus credits can be used in cost-effective nutrient removal evaluations of discharges to receiving waterbodies, especially those subjected to total maximum daily load (TMDL) limitations or defined as nutrient impaired waters (Wanielista et al., 2012). These nutrient credits can be bought, sold, and traded among various agencies, which offers attractive economic incentives for using FTWs as a BMP in stormwater management. Nutrient credit trading has become popular in the Chesapeake Bay area, where compliance with stormwater regulations has recently become more complex after the development of a Bay-wide TMDL for nitrogen and phosphorus. Nutrient credit purchasing and trading has been developed as one method in response to the Chesapeake Bay TMDL and state stormwater regulations (Cappiella et al., 2013).

3.3.9 *Temperature and Precipitation Considerations*

In order to provide a holistic assessment of nutrient reduction throughout the study, temperature, precipitation, and nutrient concentrations were documented over the study period for the Gainesville, Ruskin, and Orlando study sites and are presented in Figure 3-4. It is interesting to note that only two samples were collected on dates where the temperature was in the range of 5 to 15°C, the optimal temperature range for TN and TP reduction, observed in the study by Van de Moortel et al. (2010). There was positive TN and TP reduction rates for the sampling event at the Gainesville site on January 16, 2014. However, the sampling event on January 13, 2011, showed no substantial increases in nutrient reduction during colder temperatures, compared to the rest of the data set for the Orlando site. Due to Florida's warm climate, TN and TP reduction rates may not have been optimal and further research on the efficacy of FTWs for nutrient reduction in colder climates would be valuable.

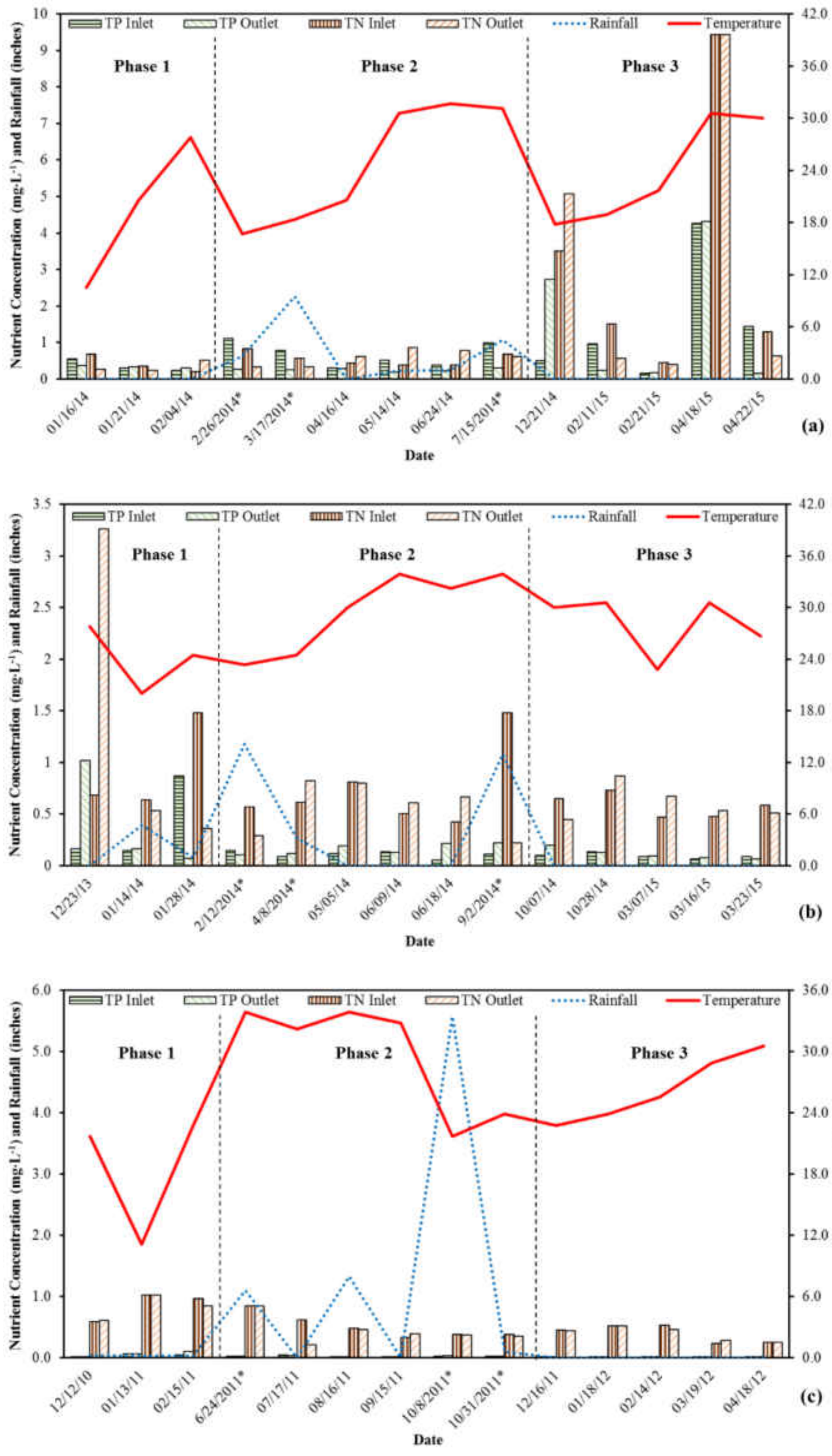

Figure 3-4. Comparative analysis of temperature and precipitation impact on FTW performance; (a) Gainesville, (b) Ruskin, and (c) Orlando; (*) Storm event sampling dates

Temperature did not appear to have a significant impact on nutrient reduction rates for this study. As seen in Figure 3-4, precipitation plays a key role for influent TN and TP concentrations. Typically following large rainfall events, stormwater runoff carries elevated concentrations of TN and TP into stormwater management systems. An example of elevated influent nutrient concentrations following rainfall events can be observed at the Gainesville pond during the February 26, March 17, and July 15, 2014, sampling dates, as well as the September 2, 2014, sampling date at the Ruskin site for TN. Despite elevated TN and TP influent concentrations, the effluent concentrations remained relatively similar to other sampling dates, which is a promising result and evidence of the FTWs capability of treating heightened nutrient influxes. The Gainesville sampling event on April 18, 2015, yielded water quality samples with extremely high values of TP and TN. This anomaly could be explained by recent fertilizer application on the adjacent residential areas, a roadway spill that carried elevated nutrient concentrations into the stormwater wet detention pond, or dumping of wastes by unwary citizens into the stormwater inlet. Nutrient concentrations at the Orlando site did not appear to be dependent on temperature and only minor fluctuations in TN concentrations can be observed resulting from changes in precipitation. Due to TP concentrations being low in the Orlando pond, it is difficult to assess the dependency of TP concentrations on either temperature or precipitation.

3.4 Final Remarks

The event-based field investigation and statistical analysis for effectiveness of FTWs at the three candidate ponds yielded valuable results. Analysis of the data from a percent reduction perspective yielded two significant results, which was TP reduction at the Gainesville pond during storm events from Phase 1 to Phase 2 and TN reduction at the Gainesville pond during non-storm events from Phase 2 to Phase 3. Percent reduction metrics alone can be misleading in determining effectiveness. According to Wright Water Engineers and Geosyntec Consultants (2007) larger influent values have been shown to reflect larger CRP values; therefore, statistical differences among influent and effluent concentrations has been recommended as a better means of evaluation.

Analysis of statistical differences among inlet and outlet concentrations of TN and TP resulted in more promising results. The FTWs proved to be significantly effective at enhancing TN reduction during storm-events, when the ponds were analyzed from a holistic perspective. More specifically, the FTWs proved significantly effective at enhancing TP reduction at the Gainesville pond during storm and non-storm events. Although the FTWs did not show significant impacts during the non-storm events for the combined data set, evidence of their effectiveness during storm events is far more important. Stormwater runoff has the most detrimental impacts when large quantities of nutrients and other pollutants are introduced to receiving waterbodies during and directly following rainfall events.

FTWs proved effective at increasing the nutrient reduction capacity of stormwater wet detention ponds and mitigating the adverse effects of stormwater pollution as it is discharged from stormwater developments to the natural environment. Due to the severity of nutrient impairment at the start of this study, specifically at the Ruskin and Gainesville sites, implementation of FTWs alone cannot restore the ponds to a pristine condition; however, over time, FTWs do enhance nutrient reduction rates and are an environmentally sustainable alternative to typical stormwater management practices. To sufficiently improve conditions at severely impaired waterbodies, such as Ruskin and Gainesville, more drastic measures can be taken, such as doubling, even tripling the

FTW coverage rate or coupling multiple BMPs to form a BMP treatment train within a stormwater wet detention pond.

3.5 References

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CHAPTER 4: COMPLEX INTERACTIONS AMONG NUTRIENTS, CHLOROPHYLL-A, AND MICROCYSTINS IN THREE STORMWATER WET DETENTIONS PONDS WITH FLOATING TREATMENT WETLANDS

4.1 Introduction

Stormwater wet detention ponds are designed to hold a permanent pool of water that provides many beneficial uses including flood mitigation, pollution prevention, downstream erosion control, increased aesthetics, and recreational uses. These ponds are a common best management practice (BMP) for managing stormwater runoff in Florida and elsewhere. However, stormwater wet detention ponds receive high nutrient loadings at times, typically following large rainfall events, resulting in eutrophication of receiving waterbodies and the formation of harmful algal blooms (HABs). One aspect that is not well understood and recently emerged as a topic of interest for aquatic ecosystems and protection of freshwater resources, is the interaction among nutrients, microcystin, and chlorophyll-a and their implications in ecosystem integrity.

Nutrients, such as nitrogen and phosphorus, are essential components to maintaining a healthy aquatic environment; however, when these nutrients are in excess they begin to have adverse effects. Excess nutrients originating from urban stormwater runoff can promote environmental issues and concerns such as eutrophication, an excess richness of nutrients in a waterbody that results in dense plant and algal growth and can lead to the death of aquatic organisms due to oxygen depletion. If sufficient nutrient removal, natural or artificial, is not provided by the stormwater wet detention pond, this buildup of excess nutrients can influence toxin-producing algal species or even cause the collapse of an aquatic ecosystem (Anderson et al., 2002).

Nitrogen- and phosphorus-containing substances are found in urban stormwater runoff originating from highways, residential areas, and grasslands in urban regions. Over-fertilization leading to nutrient-laden runoff can accelerate the eutrophication process, resulting in hypereutrophic aquatic environments. Phosphorus is often found to be the limiting nutrient for freshwater aquatic ecosystems, but increased quantities of phosphorus and nitrogen in stormwater wet detention ponds can alter the competitive relationships among terrestrial and aquatic organisms. This degradation process may result in dissolved oxygen levels falling below 2 $mg \cdot L^{-1}$, which can suffocate aquatic organisms and result in the collapse of an aquatic ecosystem (Chang et al., 2012).

Microcystins are a class of toxins produced by certain types of freshwater cyanobacteria, primarily *Microcystis aeruginosa*. As of today, more than 90 different types of microcystins have been discovered (Schmidt et al. 2014 and Pearson et al. 2010). Cyanobacterial toxins include cytotoxins as well as biotoxins, biotoxins being responsible for acute lethal, acute, chronic, and sub-chronic poisonings of wild and domestic animals and humans (Carmichael, 2001). Exposure to microcystin-contaminated water has been shown to cause acute neurotoxicity, skin irritation and, in cases of chronic exposure, even liver cancer (Pouria et al., 1998 and Fleming et al., 2002). The toxic effects of microcystins have been attributed to the inhibition of protein phosphates (Mackintosh et al., 1990), causing the collapse of the cytoskeleton and interfering with the general signal transduction mechanism in cells (Lambert at al., 1994). Confirmations of human deaths from cyanotoxins are limited to exposure through renal dialysis at a hemodialysis center in Caruaru, Brazil in 1996 (Carmichael, 2001). Traces of the microcystin toxin have been found in stormwater wet detention ponds, as our study demonstrates. Microcystins are known to be produced in large quantities during HABs, which commonly occur in stormwater wet detention ponds. Therefore, microcystin prevention is an important aspect of stormwater wet detention pond management in Florida and elsewhere.

High exogenous nutrient loading and favorable weather conditions have been considered the most important environmental factors in promoting mass development of cyanobacteria, and approximately half the algal blooms that occur prove to be toxic. Algal cells show that with increasing nitrogen concentration, the cellular microcystin to dry weight ratios increases while microcystin to protein ratios remain constant (Vezie et al., 2002). Increasing concentrations of phosphorus have been shown to slightly increase or decrease the hepatoxicity of *Microcystis*. Vezie et al. (2002) showed that growth of toxic strains of *Microcystis* was favored at high nutrient concentrations, whereas at lower nutrient concentrations, the nontoxic strains were more prevalent. This finding indicates that community competition is a major factor in discerning the toxicity of microcystin present in a waterbody. When managing stormwater wet detention ponds, the environment should be controlled to influence nontoxic strains over toxic strains by implementing BMPs aimed at lowering the total available nutrients.

An innovative and newly emerging BMP to aid nutrient removal in stormwater wet detention ponds is the installation of FTWs, a man-made ecosystem that mimics natural wetlands (Sample et al., 2013). FTWs offer an environmentally sustainable and economical approach for removing excess nutrients in stormwater wet detention ponds. Plants grow on interlocking, floating foam mats rather than at the bottom of the pond, allowing them to interact with suspended nutrients in the water column. FTWs support the growth of root systems of the floating plants, offering a large surface area in the root zone for microbial nutrient removal processes (Govindarajan, 2008) and entrapment of suspended particles (Headley and Tanner, 2006). Pollutant removal occurs through three primary mechanisms: (1) plants directly uptake nutrients from the water using a process known as biological uptake; (2) microorganisms growing on the floating mats and plant root systems break down and consume organic matter in the water through microbial decomposition; and (3) root systems filter out sediment and associated pollutants (Sample et al., 2013).

This chapter attempts to answer the following science questions through a comparative evaluation of nutrient, microcystin, and chlorophyll-a concentrations: (1) How does the correlation among total phosphorus (TP), total nitrogen (TN), microcystin, and chlorophyll-a concentrations differ across the three candidate ponds? (2) Are these correlation values influenced by whether the sampling event is episodic (storm event) or routine (non-storm event)? (3) Does one nutrient species, either TN or TP, dominate the correlation factors with microcystin and chlorophyll-a? (4) Does the implementation of FTWs for enhancing nutrient removal in stormwater wet detention ponds affect correlation values?

4.1.1 *Chapter Objectives*

The objective of this chapter is to analyze the interactions among nutrient, microcystin, and chlorophyll-a concentrations in three stormwater wet detention ponds using a Pearson correlation test. Previous research at the Orlando pond identified a negative correlation between nutrient and microcystin concentrations (Wanielista et al., 2012). During the previous study, total nitrogen concentrations fluctuated opposite to those of microcystin concentrations before and after replacing plants on the FTWs, possibly because as nutrient levels increase in stormwater wet detention ponds the algae flourish and continue to grow, thus resulting in low levels of microcystin.

As the nutrient levels begin to decrease, competition for these nutrients occurs in the stormwater wet detention pond and some algae and cyanobacteria begin to die, resulting in the release of microcystin toxins.

4.2 Methodology

For consistency and ease of reference throughout this chapter the following terminology will be used to describe the sampling time periods: (1) Phase 1: the pre-analysis sampling time period before installation of the FTWs; (2) Phase 2: the post-BMP sampling time period after installation of the FTWs; and (3) Phase 3: the sampling time period after plant replacements were performed on the FTWs. Sampling of the stormwater wet detention ponds was accomplished by collecting water quality samples at the inlet and outlet of each pond. During Phase 1, three non-storm samples were collected from each pond. During Phase 2, three non-storm and three storm samples were collected from each pond. During Phase 3, five non-storm samples were collected from each pond. Storm samples are defined in this study as water quality samples collected from the stormwater wet detention ponds during or directly following rainfall events. Storm events with total rainfall quantities greater than 0.25 inches were used as representative storm samples to ensure the quantity and quality of surface runoff would have a significant impact on the stormwater wet detention pond. By collecting storm samples during or directly following rainfall events, the effects of particulates carried into the stormwater wet detention ponds that shield light and lead to higher mortality rates over time was excluded; however, this factor may be accounted for by non-storm samples collected in the days following a storm event. Non-storm samples are defined in this study as water quality samples collected from the stormwater wet detention ponds during the inter-event dry period, the period of time between storm events. The inter-event dry period must be sufficiently long so that two rainfall events are independent of one another. For stormwater control systems, the inter-event dry period between two successive rainfall events should be greater than or equal to the time required for pollution control and be greater than the recovery time of the stormwater transport system and wet detention pond (Wanielista et al., 1991).

4.2.1 *Gainesville Pond*

This 2,363 m^2 pond is located in Gainesville, Florida, at the low point between two hills to the east and west and receives runoff from State Road 26 located directly to the south. The pond is flanked by a forest to the east and north and a residential area located to the west. The pond receives direct overland flow from the surrounding forest and residential area as well as runoff pooling at the low point of State Road 26, discharged into the pond through stormwater piping. The experimental design for this pond was divided into three phases: Phase 1 (January 2014 – February 2014), Phase 2 (February 2014 – July 2014), and Phase 3 (December 2014 – April 2015). This pond suffered from algal growth, which covered the entire surface of the pond, as well as floating debris that entered through the stormwater piping system.

Three buoyant, foam mats (Beemats, LLC) with an interlocking puzzle-cut design that enables the floating mats to be assembled in various sizes and shapes were installed in this pond. Nylon connectors were stapled onto adjacent mats to provide stability for the whole FTW system. The FTWs deployed in this pond covered roughly 5% of the pond's surface area (Figure 4-1), and a complete replacement of the FTW plants was performed on November 5, 2014. The plants selected for placement in pre-cut holes on the mats for this pond were Canna, Juncus, Blue Flag Iris, and Agrostis.

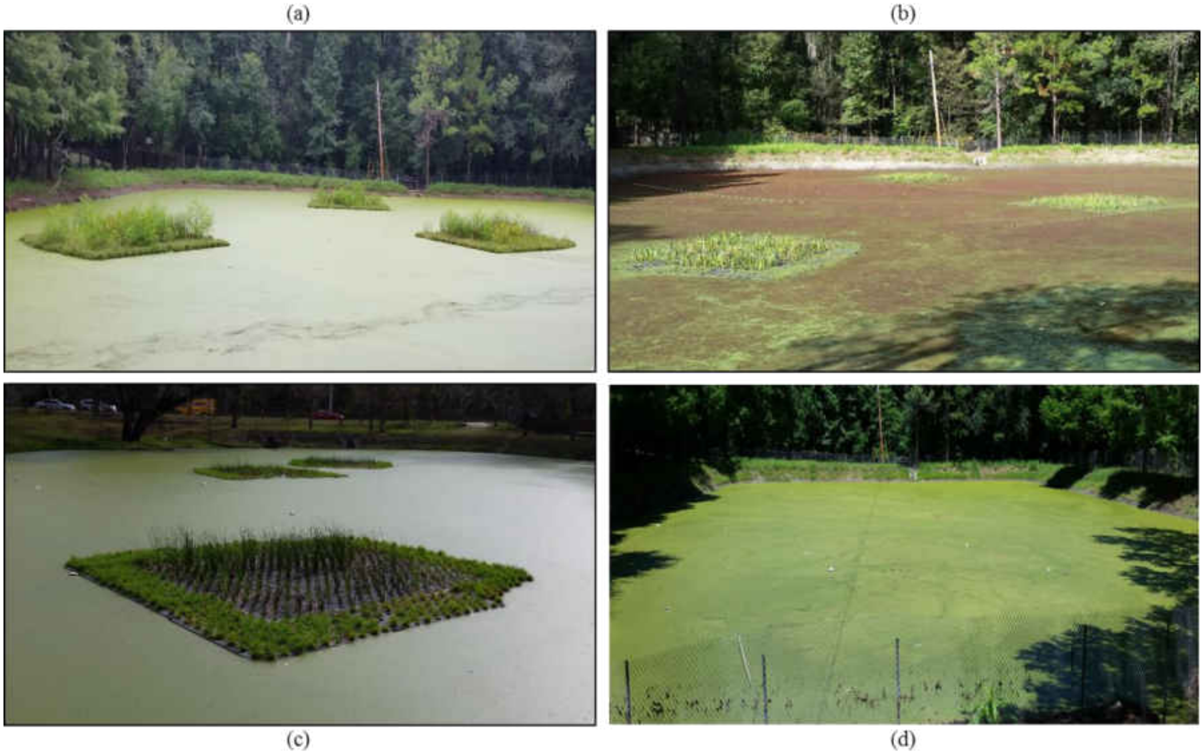

Figure 4-1. FTWs at Gainesville pond, (a) 7 months after installation, (b) after plant replacement, (c) prior to removal, and (d) after removal

4.2.2 *Ruskin Pond*

This 1,263 m^2 pond, constructed in 1994, is located in Ruskin, Florida, adjacent to a tomato field to the south and west, a commercial shopping area to the east, and a residential neighborhood to the north. The pond has excessive vegetative growth in the littoral zone, which could be explained by a high influx of nutrients flowing in from the tomato field. Similar to Gainesville pond, algal growth covered the entire surface of the pond. The experimental design period for this pond was divided into three phases as follows: Phase 1 (December 2013 – January 2014), Phase 2 (February 2014 – May 2014), and Phase 3 (October 2014 – March 2015).

The Ruskin pond utilized a buoyant, foam mat (Beemats, LLC), but due to the thick vegetative growth around and within the pond and smaller pond size, only one FTW was installed. A complete replacement of the FTW plants was performed on September 17, 2014. The FTW deployed in this pond covers roughly 5% of the pond's surface area (Figure 4-2). The plants selected for placement in pre-cut holes on the mats for this pond were Canna, Juncus, Blue Flag Iris, and Agrostis.

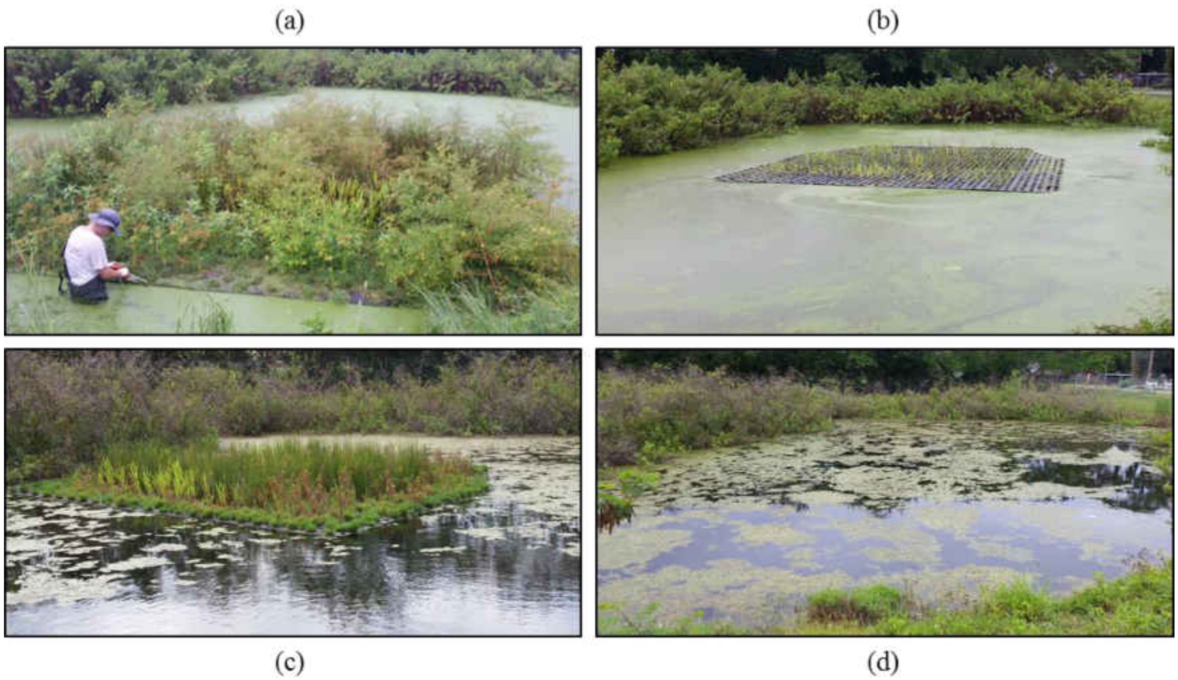

Figure 4-2. FTW at Ruskin, (a) 8 months after installation, (b) after plant replacement, (c) prior to removal, and (d) after removal

4.2.3 *Orlando Pond*

The Orlando pond, called Pond 4M locally, is a stormwater wet detention pond in Orlando, Florida, constructed in 2000. The land use surrounding the pond is classified as low density commercial, primarily composed of schools, offices, and small shopping centers on the main campus of The University of Central Florida. The pond receives stormwater runoff from areas where cars are parked for extended periods of time but with relatively low traffic flows. The pond surface area is 2,792 m^2 and is directly surrounded by woods, grassy areas, and commercial buildings. The experimental design period was divided into three phases: Phase 1 (November 2010 – April 2011), Phase 2 (April 2011 – December 2011), and Phase 3 (December 2011– April 2012).

The Orlando pond utilized three buoyant, foam mats (Beemats, LLC) to evenly distribute plants throughout the pond. The plants selected to be placed in pre-cut holes on the mats for the Orlando pond were Canna, Juncus, and Agrostis. FTWs were deployed on April 8, 2011, and covered roughly 6.4% of the pond surface area (Figure 4-3), a coverage that has been proven to be cost-efficient for FTWs in similar environmental conditions (Chang et al., 2012).

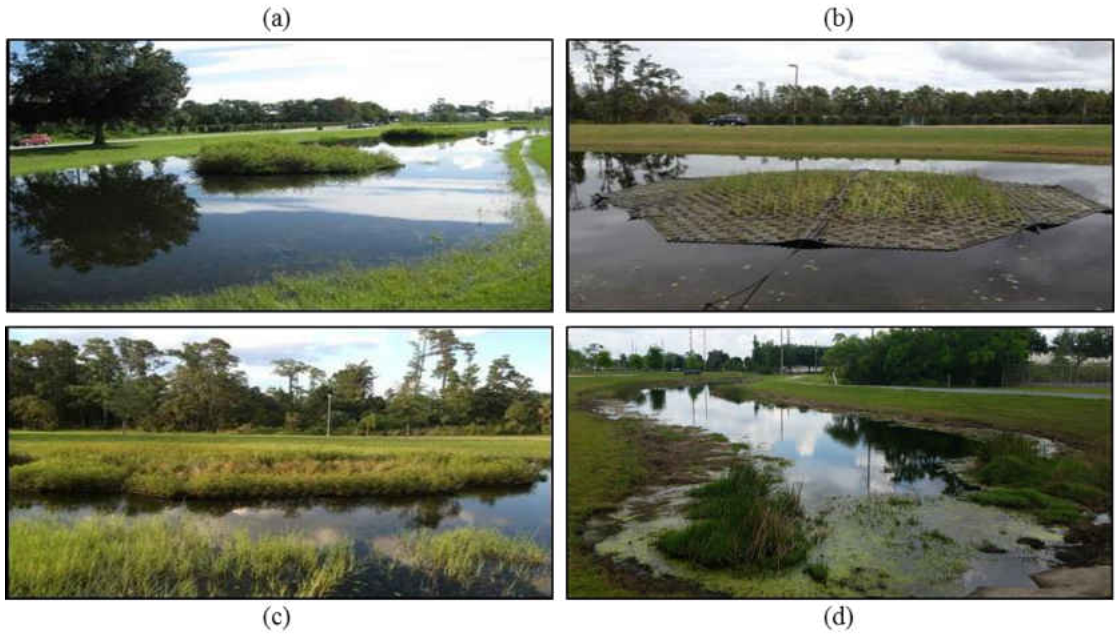

Figure 4-3. FTWs at Orlando pond in Orlando, (a) 6 months after installation, (b) after plant replacement, (c) prior to removal, and (d) after removal

4.2.4 *Comparison of the Three Ponds*

The three Florida stormwater wet detention ponds in this study each have their own unique characteristics. Through rigorous sampling of nutrient, microcystin, and chlorophyll-a concentrations at the Ruskin, Gainesville, and Orlando ponds, a Pearson Correlation test was used to produce correlation coefficient values to aid in correlation trend analysis. The FTW coverage percentage for each of the three ponds is similar, with all values falling in the range of 5 to 7%. The surroundings of the three ponds are also similar, primarily being residential, wooded areas, or highways. The shapes of the Gainesville and Ruskin ponds are similar, roughly a square design, whereas the Orlando pond is long and rectangular.

The climate of all three Florida stormwater wet detention ponds can be classified as humid subtropical with a defined rainy season that lasts from May through October, during which air-mass thundershowers build during the daytime heat and drop heavy but brief rainfall typically in the afternoon. Late summer and early fall brings decaying tropical lows that typically result in rainfall events across Florida. In October the dry season begins, which typically lasts until late April. Fronts sweep through northern and central Florida that bring winter rainfall, but the winter is often dry and sunny across much of Florida. The inter-event dry period varies significantly in Florida depending on the time of year. During the rainy season the inter-event dry period may be as short as one day, but during the dry season, may span multiple weeks.

4.2.5 *Nutrient Evaluation*

Water quality samples were collected at five locations from the inlet to outlet pipes in the Orlando pond. For the Gainesville and Ruskin ponds, water quality samples were collected at the locations of the inlet and outlet pipes. In order to measure the effectiveness of nutrient reduction with inclusion of FTWs, nutrient percentage reductions were calculated in Phase 1, Phase 2, and Phase 3 of the project. All samples were transported at 4ºC to a National Environmental Laboratory Accreditation Program (NELAP) certified laboratory called Environmental Research & Design (ERD), located in Orlando, Florida, for nutrient analysis. The percent reduction of nutrients was calculated using the water quality data collected for each of the three ponds. The following equation was utilized:

$$CRP = \frac{C_{inflow} - C_{outflow}}{C_{inflow}} * 100\% \qquad (4\text{-}1)$$

where CRP = concentration reduction percentage (%), C_{inflow} = influent concentration ($mg \cdot L^{-1}$), and $C_{outflow}$ = effluent concentration ($mg \cdot L^{-1}$).

Total organic nitrogen concentrations were evaluated using Standard Method: 4500-N(Org) C. Semi-Micro-Kjeldahl. The Kjeldahl method 4500-N(Org) C determines nitrogen in the tri-negative state. It fails to account for nitrogen in the form of azide, azine, azo, hydrazone, nitrate, nitrite, nitrile, nitro, nitroso, oxime, and semi-carbazone. Kjeldahl nitrogen is the sum of organic nitrogen and ammonia nitrogen. In the presence of sulfuric acid (H_2SO_4), potassium sulfate (K_2SO_4), and cupric sulfate ($CuSO_4$) catalyst, amino nitrogen of many organic materials is converted to ammonium. Free ammonia is also converted to ammonium. After addition of base, the ammonia is distilled from an alkaline medium and absorbed in boric or sulfuric acid. The ammonia may be determined colorimetrically, by ammonia-selective electrode, or by titration with a standard mineral acid (Standard Methods, 2011). Total nitrogen can be calculated by simply summing total Kjeldahl nitrogen (ammonia, organic, and reduced nitrogen) and nitrate-nitrite nitrogen (NO_x).

Total phosphorus concentrations were evaluated using Standard Method: 4500-P F. Automated Ascorbic Acid Reduction Method. Orthophosphates can be determined in potable, surface, and saline waters over a range of 0.001 to 10.0 mg $P \cdot L^{-1}$ when photometric measurements are made at 650 to 660 or 880 nm in a 15-mm or 50-mm tubular flow cell, respectively. Although the automated test is designed for orthophosphate only, other phosphorus compounds can be converted to this reactive form by various sample pretreatments described in Standard Methods Section 4500-P.B. Ammonium molybdate and potassium antimonyl tartrate react with orthophosphate in an acid medium to form an antimony-phosphomolybdate complex, which, on reduction with ascorbic acid, yields an intense blue color suitable for photometric measurement (Standard Methods, 2011).

4.2.6 *Microcystin Evaluation*

Microcystin samples were collected, filtered, and frozen before analysis with a microcystin and nodularin ELISA test kit. The analysis of microcystin concentrations was performed by following instructions provided by the kit manufacturer, summarized as follows: (1) add 50 µL of each sample into the wells of the test strips, using duplicates or triplicates; (2) add 50 µL of the antibody solutions to the individual wells, cover with parafilm, mix in a circular motion for 30 seconds, and then incubate at room temperature for 90 minutes; (3) decant the contents of the wells into a sink and wash the strips with 1X wash buffer solution 3 times, using 250 µL of wash buffer for each well; (4) add 100 µL of the enzyme conjugate to the individual wells, cover the wells with parafilm and mix for 30 seconds, incubate again at room temperature for 30 minutes; (5) decant the contents into a sink and wash the individual wells again with 1X wash buffer solution, using 250 µL of wash buffer for each well and each washing step; (6) add 100 µL of substrate (color) solution, cover the wells with parafilm and mix in a circular motion for 30 seconds, and then incubate again at room temperature for 20-30 minutes; (7) add 50 µL of stop solution to the wells in the same sequence as the substrate (color) solution was added; and (8) read the absorbance at 450 nm using a microplate ELISA photometer within 15 minutes after the addition of stop solution. The detection range of the microcystin analysis is 0 - 5 parts per billion (ppb).

4.2.7 *Chlorophyll-a Evaluation*

Samples were analyzed for chlorophyll-a concentrations using an Aquafluor Handheld Fluorometer and Turbidimeter, a lightweight instrument with a dual-channel capability that allows the user to measure either fluorescence or turbidity in one sample. The Aquafluor can be configured for any two out of seven channels for measurements as follows: in vivo chlorophyll-a;

cyanobacteria; turbidity; Rhodamine WT; fluorescein; ammonium; and extracted chlorophyll-a. The linear detection range of the chlorophyll-a analysis is 0 - 300 $\mu g \cdot L^{-1}$, with a minimum detection limit of 0.3 $\mu g \cdot L^{-1}$.

Inlet and outlet samples were each measured in triplicate and the average value was taken as the representative data point, a method designed to eliminate variability due to instrumentation, resulting in a more representative data point. Chlorophyll-a measurements were taken directly after collection of each sample as soon as they were transported to a lab on the campus of The University of Central Florida.

4.2.8 *Hypotheses*

The hypotheses to be tested in this chapter are as follows. (1) Correlation for TP, TN, microcystin, and chlorophyll-a concentrations are not different among the three ponds. (2) The impact of storm vs. non-storm sampling conditions has no effect on correlation among nutrients, microcystin, and chlorophyll-a. (3) One nutrient species, either TN or TP, does not control correlation values with microcystin or chlorophyll-a. (4) Installation of FTWs has no effect on correlation values among nutrients, microcystin, and chlorophyll-a. Because a single hypothesis can apply to multiple correlation tests and may be true for one correlation while false for another correlation, separate sub-hypotheses were applied for each correlation test, designated a, b, or c (Table 4-1).

Table 4-1. Hypotheses for each correlation test

Hypothesis	Nutrient-Microcystin	Nutrient-Chlorophyll-a	Microcystin-Chlorophyll-a
1	a	b	c
2	a	b	c
3	a	b	c
4	a	b	-

4.2.9 *Statistical Analysis*

The statistical analysis utilized in this chapter is the Pearson product-moment correlation coefficient, developed by Karl Pearson in the 1880s. The Pearson coefficient, sometimes referred to as Pearson's r, is a measure of linear correlation or dependence between two variables, X and Y. The variables were defined as nutrient, microcystin, and chlorophyll-a concentrations and only two of the three variables were compared against one another at a time. The Pearson coefficient is given a value between +1 and −1 inclusive, where +1 is a total positive correlation, 0 is no correlation, and −1 is total negative correlation. This test is widely used in the sciences as a measure of the degree of linear correlation between two variables (Stigler, 1989).

4.3 Results and Discussion

4.3.1 *Phase 1*

Results from sampling nutrient, microcystin, and chlorophyll-a concentrations during Phase 1 at the Gainesville, Ruskin, and Orlando pond sites are presented in Table 4-2. Concentrations for TN and TP were calculated by using the average of inlet and outlet concentrations; microcystin concentrations were calculated using the average of inlet, center, and outlet concentrations; and chlorophyll-a concentrations were calculated using the average of inlet and outlet concentrations. The inlet and outlet chlorophyll-a concentrations were taken in triplicate and averaged to obtain their value.

Table 4-2. Phase 1 nutrient, microcystin, and chlorophyll-a concentrations

Pond	Event Type	Date	TN ($mg \cdot L^{-1}$)	TP ($mg \cdot L^{-1}$)	Microcystin (ppb)	Chl-a (ppb)
Ruskin	Non-Storm	12/23/13	1.97	0.59	0.02	5.06
		01/14/14	0.58	0.16	0.05	5.35
		01/28/14	0.92	0.47	0.05	5.62
Gainesville	Non-Storm	01/16/14	0.47	0.46	0.02	1.70
		01/21/14	0.30	0.32	0.06	1.49
		02/04/14	0.36	0.27	0.01	1.43
Orlando	Non-Storm	12/12/10	0.60	0.01	0.12[a]	1.27
		01/13/11	1.02	0.06	0.03[a]	1.20
		02/15/11	0.90	0.07	0.04[a]	1.37

[a]Orlando microcystin samples were taken in March 2015 to represent missing Phase 1 data.

Results of the water quality sampling campaign during Phase 1 show a fairly consistent TN concentration at all three stormwater wet detention ponds ranging from 0.30 to 1.0 $mg \cdot L^{-1}$, with one concentration spike at the Ruskin pond on December 23, 2013, of 1.97 $mg \cdot L^{-1}$. The TP concentrations at the Ruskin and Gainesville ponds were similar, ranging from 0.10 to 0.60 $mg \cdot L^{-1}$; however, TP concentrations at the Orlando pond were much lower, with all values less than 0.10 $mg \cdot L^{-1}$. Microcystin and chlorophyll-a concentrations were similar at all three stormwater wet detentions ponds, with one exception being elevated chlorophyll-a readings at the Ruskin pond, likely explained by dense algal growth within that pond.

4.3.2 *Phase 2*

The results from sampling nutrient, microcystin, and chlorophyll-a concentrations during Phase 2 at the Gainesville, Ruskin, and Orlando pond sites are presented in Table 4-3. Similar to

Phase 1, the TN concentrations are consistent across all three ponds, with values slightly decreasing to the range of 0.30 to 0.90 mg·L^{-1}. TP concentrations are still very low within the Orlando pond and have decreased at both the Gainesville and Ruskin ponds, which is promising evidence of FTWs abilities to reduce nutrients within stormwater wet detention ponds. Installation of FTWs has increased the concentration of microcystin toxins, specifically at the Ruskin pond during Phase 2. This is due to competition for nutrients within the HABs, resulting in the death of some algal species. Chlorophyll-a concentrations remained consistent at the Orlando pond during Phase 2; however, concentrations slightly decreased and slightly increased at the Ruskin and Gainesville ponds, respectively.

Table 4-3. Nutrient, microcystin, and chlorophyll-a concentrations and precipitation

Pond	Event Type	Date	TN (mg·L^{-1})	TP (mg·L^{-1})	Microcystin (ppb)	Chl-a (ppb)	Precipitation (in.)
Ruskin	Non-Storm	05/05/14	0.81	0.16	0.18	2.31	-
		06/09/14	0.56	0.13	0.17	4.36	-
		06/18/14	0.54	0.13	0.04	6.33	-
	Storm	02/12/14	0.43	0.13	0.01	3.03	1.18
		04/08/14	0.72	0.10	0.10	3.99	0.27
		09/02/14	0.85	0.17	0.09	3.31	1.08
Gainesville	Non-Storm	04/16/14	0.52	0.29	0.07	1.76	-
		05/14/14	0.62	0.35	0.16	2.20	-
		06/24/14	0.58	0.30	0.10	2.34	-
	Storm	02/26/14	0.58	0.68	-	3.09	0.63
		03/17/14	0.46	0.51	0.01	2.99	1.30
		07/15/14	0.64	0.65	0.03	2.73	1.10
Orlando	Non-Storm	07/17/11	0.41	0.04	0.01	1.05	-
		08/16/11	0.47	0.01	0.07	1.26	-
		09/15/11	0.36	0.01	0.05	1.43	-
	Storm	06/24/11	0.84	0.02	0.14	1.68	1.10
		10/08/11	0.37	0.02	0.02	1.01	1.11
		10/31/11	0.36	0.02	0.13	1.17	0.27

4.3.3 *Phase 3*

An additional five non-storm water quality samples were collected at each stormwater wet detention pond following plant replacements on the FTWs. Replacing mature plants on FTWs is a necessary maintenance practice to ensure mature plants do not die and reintroduce nutrients into the water column. Mature plants were removed from the FTWs, bagged for future disposal or other reuse applications, and replaced with seedlings. It is important to characterize the correlation among nutrients, microcystin, and chlorophyll-a over the three study phases so that a holistic understanding of FTW impact on aquatic ecosystems is achieved. The results of Phase 3 water quality sampling are presented in Table 4-4.

Table 4-4. Phase 3 nutrient, microcystin, and chlorophyll-a concentrations

Pond	Event Type	Date	TN ($mg \cdot L^{-1}$)	TP ($mg \cdot L^{-1}$)	Microcystin (ppb)	Chl-a (ppb)
Ruskin	Non-Storm	10/07/14	0.55	0.15	0.24	3.31
		10/28/14	0.80	0.13	0.24	4.33
		03/07/15	0.57	0.09	0.17	3.73
		03/16/15	0.51	0.07	0.49	2.99
		03/23/15	0.55	0.08	0.17	5.26
Gainesville	Non-Storm	12/21/14	4.28	1.61	0.15	2.05
		02/11/15	1.03	0.59	0.09	1.67
		02/21/15	0.43	0.17	0.10	1.17
		04/18/15	9.43	4.30	0.02	1.51
		04/22/15	0.97	0.80	0.66	1.12
Orlando	Non-Storm	12/16/11	0.44	0.01	0.02	-
		01/18/12	0.51	0.02	0.02	-
		02/14/12	0.49	0.01	0.08	-
		03/19/12	0.25	0.01	0.11	-
		04/18/12	0.25	0.01	0.30	-

4.3.4 *Correlation Analysis of Nutrient, Microcystin, and Chlorophyll-a*

The nutrient-microcystin, microcystin-chlorophyll-a, and nutrient-chlorophyll-a correlation values are presented in Tables 4-5, 4-6, and 4-7, respectively. A visual representation of the nutrient, microcystin, and chlorophyll-a correlation trends for the Ruskin, Gainesville, and Orlando pond sites (Figures 4-4, 4-5, and 4-6, respectively) is also presented. Precipitation data were included to provide a comparison among differing rainfall events and depict how rainfall intensity may affect correlation trends.

Table 4-5. Nutrient-microcystin correlation values

	Ruskin			Gainesville			Orlando		
	Storm	Non-Storm	Combined	Storm	Non-Storm	Combined	Storm	Non-Storm	Combined
Total Nitrogen	-0.22	-0.42	-0.32	-0.28	-0.13	-0.08	-0.25	-0.42	-0.27
Total Phosphorous	-0.42	-0.55	-0.44	-0.12	-0.08	-0.05	-0.66	-0.36	-0.35

Table 4-6. Microcystin-chlorophyll-a correlation values

Ruskin			Gainesville			Orlando		
Storm	Non-Storm	Combined	Storm	Non-Storm	Combined	Storm	Non-Storm	Combined
-0.15	-0.70	-0.46	-0.36	-0.31	-0.37	0.52	0.33	0.52

Table 4-7. Nutrient-chlorophyll-a correlation values

	Ruskin			Gainesville			Orlando		
	Storm	Non-Storm	Combined	Storm	Non-Storm	Combined	Storm	Non-Storm	Combined
Total Nitrogen	0.07	0.16	0.20	-0.08	-0.01	-0.17	0.55	0.04	0.44
Total Phosphorous	0.53	0.35	0.37	0.86	-0.07	-0.12	0.02	-0.10	-0.09

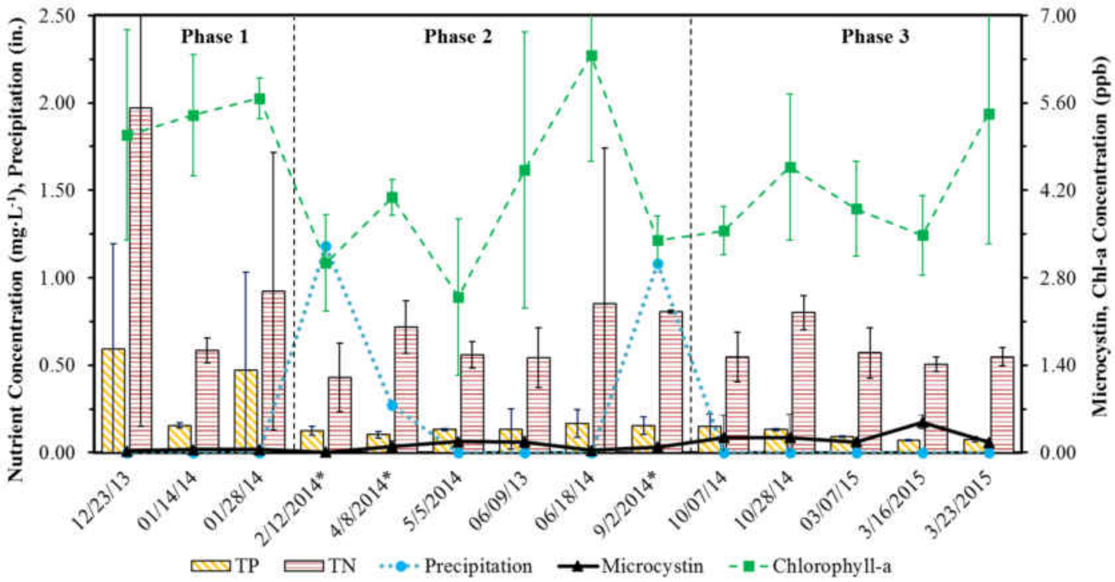

Figure 4-4. Data trends for Ruskin: TP (Yellow), TN (Red), Microcystin (Black), Chlorophyll-a (Green), Precipitation (Blue); Storm event sampling date (*)

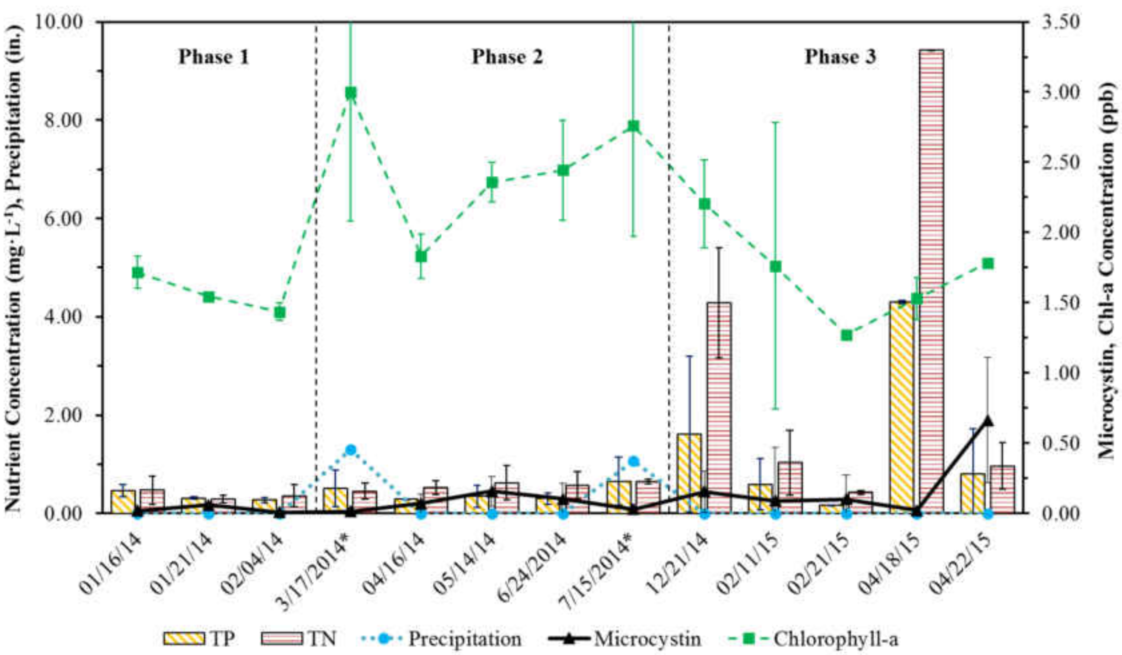

Figure 4-5. Data trends for Gainesville: TP (Yellow), TN (Red), Microcystin (Black), Chlorophyll-a (Green), Precipitation (Blue); Storm event sampling date (*)

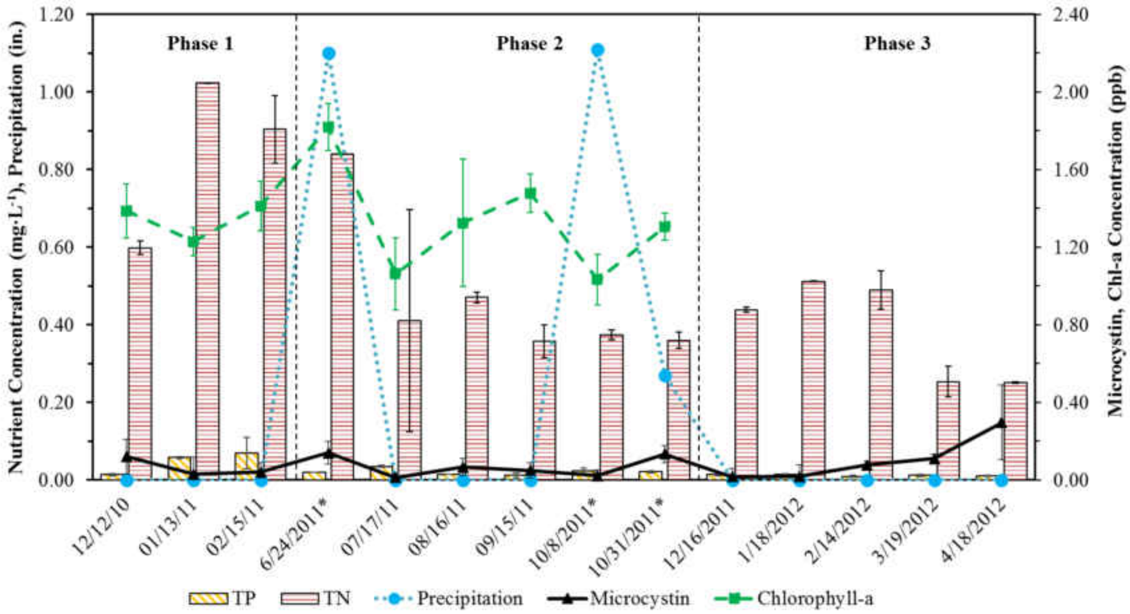

Figure 4-6. Data trends for Orlando: TP (Yellow), TN (Red), Microcystin (Black), Chlorophyll-a (Green), Precipitation (Blue); Storm event sampling date (*)

4.3.5 *Statistical Accuracy*

Calculation of a confidence interval for the Pearson coefficient is complicated, but can be achieved through use of Fisher's z-transformation. By converting the Pearson coefficient (r) to z′, a confidence interval can be calculated in terms of z′, which can be converted back to r. For example, the Pearson r value for TN and microcystin correlation at the Gainesville site for combined sampling events is 0.49, corresponding to a z′ value equal to 0.54 with lower and upper limits of 0.0138 and 1.058, respectively, at the 80% confidence interval. Converting this confidence interval back to r at the 80% confidence interval yields lower and upper limits equal to 0.014 and 0.785, respectively. Thus, for a Pearson correlation value of 0.49, the population correlation (ρ) at the 80% confidence interval is $0.014 \leq \rho \leq 0.785$. The range of the confidence interval is attributed to the number of samples collected and although the range is wide, the focus of this study is to pinpoint the overall trend of nutrient, microcystin, and chlorophyll-a interactions, which can be accomplished.

4.3.6 *Ruskin*

The correlation trend of nutrient and microcystin concentrations at the Ruskin pond site was negative for both TN– and TP–microcystin correlations. The negative correlation between TP and microcystin concentrations was stronger than for TN (Table 4-5). For example, the correlation values for TN–microcystin were −0.22 and −0.42 for storm and non-storm events, respectively; however, the TP–microcystin correlation values were −0.42 and −0.55 for storm and non-storm events, respectively, evidence of a stronger negative correlation.

The correlation trend of microcystin and chlorophyll-a concentrations was negative for both storm and non-storm conditions. Correlation values of −0.15 and −0.70 for storm and non-storm events, respectively (Table 4-6), reveal a stronger negative correlation between microcystin and chlorophyll-a during non-storm events when compared to storm events. The correlation trend of nutrient and chlorophyll-a concentrations was positive for both TN and TP, although the correlation was again stronger for TP. The TN–chlorophyll-a correlation values were only slightly positive at 0.07 and 0.16 for storm and non-storm events, respectively, whereas the TP–chlorophyll-a relationship showed a much stronger positive correlation with values of 0.53 and 0.35 for storm and non-storm events, respectively.

4.3.7 *Gainesville*

The negative correlation values between TP–microcystin concentrations at the Gainesville pond ranged from −0.12 to −0.08 for storm and non-storm events, respectively. The correlation between TN–microcystin concentrations follows a similar pattern to TP–microcystin, with values ranging from −0.28 to −0.13 for storm and non-storm events, respectively. Note that correlation values for both TN and TP were more negative during storm events when compared to non-storm events. This finding suggests that nutrients introduced into the stormwater wet detention pond following rainfall events created an environment of minimal death due to a surplus of nutrients, resulting in a minimal release of microcystin toxins.

The correlation value for microcystin–chlorophyll-a concentrations at Gainesville is similar when comparing storm to non-storm conditions. The microcystin–chlorophyll-a correlation value ranged from −0.36 to −0.31 for storm and non-storm conditions, respectively. Similar to the nutrient–microcystin correlations values previously discussed, these values are more negative for samples collected during storm events.

An interesting pattern occurred at the Gainesville site for nutrient–chlorophyll-a interactions (Table 4-7). For the TN–chlorophyll-a correlation, values ranged from −0.08 to −0.01 for storm and non-storm events, respectively. TP–chlorophyll-a correlations were almost opposite, with values ranging from 0.86 to −0.07 for storm and non-storm events, respectively. Analysis of these results suggests nitrogen concentration fluctuations play little role in determining the concentration of chlorophyll-a. Phosphorus appears to be the dominant nutrient species when determining chlorophyll-a levels, depicted by the 0.86 correlation value during storm events.

4.3.8 *Orlando*

The correlation value of nutrient–microcystin concentrations was negative for both TN and TP nutrient species. The TN–microcystin correlation value ranged from −0.25 to −0.42 for storm and non-storm events, respectively. A strong negative correlation value was found between TP–microcystin concentrations, with values ranging from −0.66 to −0.36 for storm and non-storm events, respectively.

The microcystin–chlorophyll-a correlation trend was positive and relatively similar for both storm and non-storm conditions, with values of 0.52 and 0.33, respectively. This finding is evidence of a positive correlation between microcystin and chlorophyll-a concentrations independent of the sampling conditions at the Orlando pond site.

The correlation trend of nutrient–chlorophyll-a concentrations at Orlando pond was difficult to classify. Correlation values (Table 4-7) showed a generally positive trend for TN–chlorophyll-a concentrations. Evidence suggested that the TP–chlorophyll-a correlation was neutral or slightly negative, with values ranging from 0.02 to −0.10 for storm and non-storm events, respectively. The TN–chlorophyll-a correlation had a stronger positive value of 0.55 during storm events but a more neutral value of 0.04 for non-storm events.

4.3.9 *Nutrient-Microcystin*

Analogous and unique trends exist for nutrient, microcystin, and chlorophyll-a correlations across each of the three ponds. A negative correlation was found between nutrient and microcystin concentrations for both storm and non-storm conditions across all three ponds (Table 4-5). Evidence suggests TP is the dominant nutrient species in correlation with microcystin concentrations, specifically at the Ruskin and Orlando sites, implying these two ponds are phosphorus limiting, meaning as phosphorus concentrations begin to decrease, competition for nutrients results in the death of some algal and cyanobacteria species. The negative correlation among TP–microcystin concentrations was not impacted by sampling conditions. A negative correlation was also found between TN and microcystin concentrations for both storm and non-storm events at all three stormwater wet detention ponds. Overall, the data indicate a negative correlation between nutrient and microcystin concentrations at the three stormwater wet detention ponds, with TP being the dominant nutrient species at the Ruskin and Orlando sites. With respect to TP–microcystin correlations, Hypothesis 1a and 2a were supported, and Hypothesis 3a was disproven because evidence suggests TP is the dominant nutrient species in correlation with microcystin concentrations (Table 4-5).

4.3.10 *Nutrient-Chlorophyll-a*

A positive correlation trend exists between nutrient and chlorophyll-a concentrations across all three ponds. TP is the dominant nutrient species in correlation with chlorophyll-a concentrations, specifically at the Ruskin and Gainesville sites. A positive correlation between TP and chlorophyll-a concentrations for both non-storm and storm conditions was found across all three ponds, with the exception of Orlando and Gainesville non-storm events. Although the majority of correlation values between TN and chlorophyll-a concentrations were also positive, the correlation was much stronger between TP and chlorophyll-a. For example, at Ruskin the TN–chlorophyll-a correlation values ranged from 0.07 to 0.16 for storm and non-storm events, respectively, while TP–chlorophyll-a correlation values ranged from 0.53 to 0.35 for storm and non-storm events, respectively, evidence of a stronger correlation.

Noteworthy is that the TP–chlorophyll-a correlation values were all stronger during storm events compared to non-storm events. This result is not unexpected because during and directly following rainfall events, large quantities of nutrients are carried into the stormwater wet detention ponds by surface runoff, leading to the proliferation of algal populations that directly correspond to elevated chlorophyll-a concentrations. Based on these results, with respect to TP–chlorophyll-a correlations, Hypothesis 1b was proven true; Hypothesis 2b was disproven because nutrient–chlorophyll-a correlation values were stronger for storm events when compared to non-storm events; and Hypothesis 3b was disproven because TP again was the dominant nutrient species in correlation with chlorophyll-a concentrations.

4.3.11 *Microcystin-Chlorophyll-a*

The correlation between microcystin and chlorophyll-a concentrations was not as discernible as the previous two cases. A negative correlation was observed at Ruskin, with values ranging from −0.15 to −0.70 for storm and non-storm events, respectively; however, at the Orlando pond a positive correlation was found, with values ranging from 0.52 to 0.33, respectively. At the Gainesville pond site, a negative correlation of −0.36 and −0.31 was found for storm events and non-storm events, respectively. These results reveal that site-specific environmental factors dictate the correlation direction, positive or negative, for these stormwater wet detention ponds.

Flourishing algal and cyanobacteria populations correspond to an increase in chlorophyll-a concentrations. Microcystin concentrations do not correlate the same with algal and cyanobacterial population growth, however, possibly due to multiple factors. (1) A multitude of algal and cyanobacteria species are present and not all produce the microcystin toxin. (2) The algal and cyanobacteria populations respond to nutrient levels by two pathways: (a) following a storm event, initial growth from elevated nutrient input is not impeded by competition for nutrients, which can lead to an environment of minimal death of microcystin-producing species and therefore minimal microcystin concentrations; and (b) following a storm event, now considered a non-storm environment, the population of aquatic nutrient consumers reaches a competitive threshold, resulting in the death of some species. Understanding which species may out-compete the other is crucial to understanding if microcystin toxins will be released. Microcystin–chlorophyll-a correlations may be dependent on the age and type of algal populations present in the pond as well as the availability of nutrients. The relationship between storm events and eventual detection of the microcystin toxin likely follows a lag pattern, with the release of microcystin occurring some period of time after a storm event, once the nutrients introduced into the aquatic environment by surface runoff have become depleted. This relationship is difficult to characterize because the inter-event dry period in Florida can vary dramatically depending on the time of year.

The differences observed in this study are likely due to site-specific characteristics, such as biological, chemical, and physical parameters, along with the hydrological fluctuations and stormwater runoff constituents for the different candidate sites. After evaluating these results, Hypothesis 1c was disproved. Hypothesis 2c was proven true at the Ruskin, Gainesville, and Orlando sites. Hypothesis 3c is not applicable for the microcystin–chlorophyll-a correlation.

4.3.12 *Phase 3 Correlations*

There is one phenomenon observed at the Gainesville pond that merits further discussion. The sampling event on April 18, 2015, showed highly elevated nutrient concentrations, not observed during any other sampling event during this study. This water quality sample yielded a TN concentration of 9.43 $mg \cdot L^{-1}$ and a TP concentration of 4.30 $mg \cdot L^{-1}$. These excessive concentrations could be explained by over-fertilization of the adjacent residential areas, a roadway spill that carried elevated nutrient concentrations into the stormwater wet detention pond, or dumping of wastes by unwary citizens into the stormwater inlet. What is important from these elevated nutrient concentrations is the microcystin concentration observed four days later. The water quality sample taken on April 22, 2015, resulted in a microcystin concentration of 0.66 ppb, the highest concentration observed at any site throughout the study. This finding shows the elevated nutrient concentrations documented on April 18 likely caused a rapid expansion in algal population, followed shortly after by a population collapse when nutrient levels could no longer sustain the enlarged algal population. This finding is valuable and shows that within one week of elevated nutrient concentrations entering a stormwater wet detention pond or receiving waterbody, there exists a series of events characterized by algal population expansion, followed by a population collapse, followed by elevated microcystin concentrations which may prove fatal to aquatic organisms. This finding highlights the importance of ensuring excess nutrients are removed from stormwater runoff prior to entering receiving waterbodies and shows there is limited time following an elevated nutrient influx before the harmful effects are observable in the aquatic environment.

4.3.13 *FTWs Impact on Correlation*

The primary purpose of implementing FTWs is to enhance the nutrient reduction capacity of stormwater wet detention ponds. This section discusses the correlation between nutrient and microcystin concentrations, as well as nutrient and chlorophyll-a concentrations to assess the impact of FTWs on nutrient–microcystin (Table 4-8) and nutrient–chlorophyll-a (Table 4-9) correlations from Phase 1 to Phase 3 conditions.

Table 4-8. Nutrient-microcystin correlation values

	Ruskin			Gainesville			Orlando		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Total Nitrogen	-0.97	0.53	-0.27	-0.61	0.48	-0.43	-0.98	0.57	-0.77
Total Phosphorous	-0.71	0.26	-0.28	-0.10	-0.68	-0.35	-0.96	-0.32	-0.60

Table 4-9. Nutrient-chlorophyll-a correlation values

	Ruskin			Gainesville			Orlando		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Total Nitrogen	-0.74	-0.40	0.33	0.85	-0.08	0.35	-0.14	0.77	-
Total Phosphorous	-0.29	-0.32	-0.16	1.00	0.86	0.25	0.32	-0.52	-

The most prominent impact FTWs had on nutrient-microcystin correlation occurred at the Ruskin pond site. During Phase 1 a negative correlation was found between microcystin and both TN and TP; however, during Phase 2 the correlation values switched to positive values (Table 4-8). Then during Phase 3, the correlation values returned to having a negative value. The Gainesville pond was not as dramatically impacted by implementation of the FTWs, but, similar to Ruskin, the TN–microcystin correlation switched from negative (during Phase 1) to positive (during Phase 2) and then back to negative (during Phase 3). This phenomenon was also observed at the Orlando pond, where TN–microcystin correlation changed from negative (during Phase 1) to positive (during Phase 2) and then back to negative (during Phase 3). This result is intriguing because as evidence suggests, implementation of FTWs seems to reverse the natural correlation between nitrogen and microcystin concentrations present in stormwater wet detention ponds directly following installation; however, correlation returns to the natural trend following plant replacement. These results indicate that Hypothesis 4a was disproven at the Ruskin, Gainesville, and Orlando pond sites, specifically for the TN–microcystin correlation.

Evidence suggests the implementation of FTWs at the Ruskin pond has had a negligible impact on nutrient–chlorophyll-a correlation, with both TN– and TP–chlorophyll-a correlation values remaining negative from Phase 1 to Phase 3 conditions. The Gainesville pond showed a similar result with a positive correlation for TP from Phase 1 to Phase 3; however, the TN–chlorophyll-a correlation varied in direction and switched from 0.85 (Phase 1) to −0.08 (Phase 2) to 0.35 (Phase 3), which could be explained by Gainesville pond being phosphorus limited. Due to a decrease in phosphorus concentrations during Phase 2, the impact of fluctuating nitrogen concentrations on algal and cyanobacteria populations becomes negligible, thus resulting in the negative, even slightly neutral, correlation value for TN in Phase 2.

An interesting phenomenon occurred at the Orlando pond following installation of FTWs. The TN–chlorophyll-a correlation switched from negative during Phase 1 (−0.14) to positive in Phase 2 (0.77), and the TP–chlorophyll-a correlation value switched from positive during Phase 1 (0.32) to negative in Phase 2 (−0.52). Note that TP concentrations were present at very low concentrations during the study at the Orlando site, which played a role in this result. Due to low phosphorus concentrations at Orlando pond, the stormwater wet detention pond was likely phosphorous-limited, which explains the absence of algae at the pond, compared to the Ruskin and Gainesville sites. The implementation of FTWs and the corresponding decrease in nitrogen concentrations corresponds directly to a decrease in chlorophyll-a concentrations, which explains the switch to a positive correlation value in Phase 2 at Orlando pond. After evaluation of these results, Hypothesis 4b was proven true for nutrient–chlorophyll-a correlations at Ruskin pond but disproven at Orlando pond. Hypothesis 4b was proven true for the TP–chlorophyll-a correlation at Gainesville pond but disproven for the TN–chlorophyll-a correlation.

4.3.14 *Nutrient Management in Stormwater Wet Detention Ponds*

Previous research by the Florida Department of Transportation (FDOT) identified a target nitrate (NO_3-N) concentration of 0.35 mg·L^{-1} for Florida fresh waterbodies, specifically within the Silver Springs springshed. This concentration was based on extensive data collected from 1990 to 2007 and was chosen to be protective, such that it would precede the necessary concentration for extensive periphyton (a complex mix of algae, cyanobacteria, microbes, and detritus) growth. A study by Florida LAKEWATCH found Florida lakes to be distributed into four trophic states based on TP concentrations. Lakes with TP concentrations less than 0.015 mg·L^{-1} where found to be oligotrophic (very low levels of biological productivity); lakes with TP concentrations between 0.015 and 0.025 mg·L^{-1} where found to be mesotrophic (moderate levels of biological productivity); lakes with TP concentrations between 0.025 and 0.10 mg·L^{-1} where found to be eutrophic (moderately high levels of biological productivity); and lakes with TP concentrations greater than 0.10 mg·L^{-1} where found to be hypereutrophic (very high levels of biological productivity).

Throughout our study, TN concentrations were predominantly above the target concentration of 0.35 mg·L^{-1}. The stormwater wet detention ponds can be classified as eutrophic (Orlando) and hypereutrophic (Ruskin and Gainesville) based on average TP concentrations. Therefore, additional BMPs or increased FTW coverage rates are required for significant removal of algae in stormwater wet detention ponds.

Nutrient over-enrichment in these ponds drives water quality deterioration on a long-term basis, and widespread application of fertilizers in urban and agricultural crop fields can trigger the growth of toxic cyanobacterial genus *Microcystis.* These issues have been historically addressed by controlling TP inputs. Management and research are generally based on the premise that phosphorus is the limiting factor in freshwater productivity, resulting in HAB formation and microcystin production, as discussed earlier; however, recent studies indicate HAB formation might be tied to combined nitrogen and phosphorus additions (Paerl et al., 2011; Wilhelm et al., 2011). This regime shift has strong implications in relation to TN/TP ratios. The toxic cynobacterial genus *Microcystis* often dominates in nutrient-sensitive systems despite phosphorus-focused controls (Paerl et al., 2014). Given that members of this genus cannot fix atmospheric N_2 (i.e., convert N_2 to ammonia), the growth of *Microcystis* requires combined nitrogen sources (i.e., ammonia, organic nitrogen, or nitrate) (Paerl et al., 2014). Such complexity can be validated by the fact that some of the correlations were mixed (Table 4-5). In the Orlando pond, TN was more strongly correlated with chlorophyll-a concentration than TP for storm conditions, whereas at Gainesville the opposite was true. This finding reflects the key role of nitrogen in this record because more TN can be added to the pond during storm events, yet it may also suggest that other factors are at play in controlling chlorophyll-a concentration after storm events that were not captured in this correlation study. Because nutrient concentrations varied across each of the three stormwater ponds, it is difficult to conclude that only one nutrient species is the controlling factor for chlorophyll-a or microcystin concentrations in these ponds. Many other environmental variables (such as iron enrichment, seasonality effect, and climate change) could contribute and have effects on nutrient, chlorophyll-a, and microcystin concentrations and should be explored in future research (Paerl and Paul, 2011).

Obvious trends of peak values of microcystin occur in the spring and summer seasons (from March to July) in Florida due to frequent storms. HAB control requires inhibiting algal growth during this period, and technical support should develop ecological engineering approaches when cyanobacteria are vulnerable to foraging species. New BMPs trace pre-bloom algal distribution so that proactive stormwater treatments need only be implemented within algae concentrated areas in a cost-effective, forward-looking, and risk-informed manner. This study showed that BMPs such as FTWs should be used as a proactive engineering strategy to prevent the formation of HABs instead of using reactionary measures to control existing HABs (i.e., manual, mechanical, or chemical removal). Once HABs have formed, the release of microcystin toxins is inevitable and will occur either when nutrient loadings to the pond have decreased, resulting in a depletion of available nutrients and the death of some algal species, or as a result of implementing BMPs aimed at removing nutrients. In this regard, the goal of stormwater wet detention pond management should be geared toward preventing the formation of HABs to minimize the presence of microcystin toxins in the aquatic environment. Supportive laws and government policies that maintain continuous monitoring and assessment of these waterbodies are necessary.

4.4 Final Remarks

The correlation among nutrient, microcystin, and chlorophyll-a concentrations are complex and can vary depending on site specific characteristics and environmental factors. The results of this research showed how correlation trends can vary depending on sampling conditions (storm vs. non-storm) and how the implementation of FTWs in stormwater wet detention ponds may influence microcystin and chlorophyll-a concentrations. The results identified certain nutrient species, in this case phosphorus, to be more influential in controlling the correlation values among microcystin and chlorophyll-a concentrations. Understanding the ecological impact of nutrient removal as a result of FTW implementation and the interactions among different stormwater wet detention pond variables is essential to maintaining a healthy and efficient stormwater management system. The interaction between nutrients and microcystin toxins is also vital to managing stormwater wet detention ponds targeted for stormwater reuse strategies, notably for drinking water applications.

4.5 References

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CHAPTER 5: CONCLUSIONS

Moving forward in stormwater management, innovative and affordable BMPs can be implemented in many applications for pollutant removal and protection of freshwater resources. Many of today's obstacles in stormwater management can be solved through natural solutions; therefore, learning from nature should be a key aspect of stormwater management. Application of chemicals, such as copper sulfate, can be used to control algal blooms in stormwater wet detention ponds and other waterbodies; however, these chemical often have unintended adverse consequences and can destroy delicate ecological balances. Utilization of FTWs can provide substantial nutrient removal in stormwater wet detention ponds and help protect receiving waterbodies from excess nutrient loading through natural solutions, as demonstrated in this thesis. Use of BMPs in urban areas can help restore pre-development hydrologic and ecological conditions, which are often overlooked and degraded as a result of urban development.

BMPs can be utilized in developing and existing urban areas to create networks of LID. These networks of LID are composed of natural and constructed areas and are designed to mimic pre-development hydrologic and ecological conditions. LID offers the potential to capture, treat, and infiltrate stormwater at the source. Although LID is a well-tested and proven technique for stormwater management, the widespread integration into urban areas is still non-existent. This issue arises from policies and regulations surrounding the use of LID. Governmental policies and regulations should be aimed at encouraging, even requiring, the use of LID in urban areas. A good example of this is the use of LID, specifically green roofs, in Germany. The German government encourages public participation and even offers incentives for those individuals who choose to integrate LID on private property. The majority of German households are charged for stormwater services based on an estimate of the stormwater burden generated from their properties, known as an individual parcel assessment. Land-use decisions, such as permeable pavement and greenroofs, have major impacts on the amount of stormwater leaving a property and create incentives for individuals to incorporate LID on their property. These stormwater fees create economic incentives that encourage LID where it can manage stormwater. The United States can learn many lessons from foreign countries to encourage future development and implementation of LID in urban areas. Policies must start small and be implemented in many stages and integrated across many sectors and levels of government to ensure successful results. Also, policies should be communicated with the public to foster citizen participation and encourage the use of LID at the local scale. In summary, governments should take proactive and aggressive measures to ensure the use of LID, which will become an essential component of urban areas as the rate of urbanization and demand for freshwater resources continues to grow.

Stormwater wet detention ponds hold a permanent pool of water and offer many beneficial uses including flood mitigation, pollution prevention, downstream erosion control, increased aesthetics, and recreational uses. Nutrient reduction efficiency is generally low in stormwater wet detention ponds in urban areas. To enhance nutrient reduction, FTWs can be installed in wet detention ponds to offer an innovative solution toward naturally removing excess nutrients and aiding in stormwater management. This thesis assessed nutrient reduction in three Florida stormwater wet detention ponds where FTWs were installed. Both storm event and non-storm event sampling campaigns were carried out at the three ponds located in Ruskin, Gainesville, and Orlando. Most notably, nutrient reduction rates after installation of the FTWs reached levels of 33% for total nitrogen at the Ruskin pond during storm events, 71% for total phosphorus at the

Gainesville pond during storm events, and 17% for total nitrogen at the Orlando pond during non-storm events.

To improve the stormwater reuse potential, this thesis assessed nutrient, microcystin, and chlorophyll-a interactions in three Florida stormwater wet detention ponds containing FTWs. The results showed a salient negative correlation between total phosphorus and microcystin concentrations for both storm and non-storm events across all three ponds. The dominant nutrient species in correlation was total phosphorus, which correlated positively with chlorophyll-a concentrations at all ponds and sampling conditions, with the exception of Orlando non-storm events. These results showed a correlation conditional to the candidate pond and sampling conditions for microcystin and chlorophyll-a concentrations. Understanding the ecological impact of nutrient removal as a result of FTW implementation and the interactions among different stormwater wet detention pond variables is essential to maintaining an efficient stormwater management system. The interaction between nutrients and microcystin toxins is also vital to managing stormwater wet detention ponds targeted for stormwater reuse strategies, most notably for drinking water applications. This study highlighted the importance of implementing proactive BMPs to prevent the formation of HABs and minimize the presence of microcystin toxins in stormwater wet detention ponds and receiving waterbodies.

Applying environmentally sustainable BMPs in urban areas for stormwater management can both decrease pollutant loading to receiving waterbodies and protect freshwater resources for many reuse applications. Further research and advancements may be made to the work presented in this thesis to increase accuracy, efficiency, and usability.

APPENDIX: PUBLISHED MATERIALS AND MATERIALS UNDER REVIEW

Chapters 3 and 4 of this thesis incorporate material that has been accepted for publication or is currently published as follows:

Chapter 3

Hartshorn, N., Marimon, Z., Xuan, Z., Chang, N.B., Wanielista, M., 2015. Effect of Floating Treatment Wetlands on the Control of Nutrients in Three Stormwater Wet Detention Ponds. *Journal of Hydrologic Engineering, ASCE*, Accepted for publication.

Chapter 4

Hartshorn, N., Marimon, Z., Xuan, Z., Cormier, J., Chang, N.B., Wanielista, M, 2015. Complex interactions among nutrients, chlorophyll-a, and microcystins in three stormwater wet detention basins with floating treatment wetlands. *Chemosphere*, 144 (2016): 408-419.