COMPARING THE CONDITIONS AND DESIGN OF STORMWATER DETENTION BASINS BUILT BETWEEN 1970 AND 2011 TO ESTIMATE SERVICE LIFE

By

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ABSTRACT OF THE THESIS

"COMPARING THE CONDITIONS AND DESIGN OF STORMWATER DETENTION BASINS BUILT BETWEEN 1970 AND 2011 TO ESTIMATE SERVICE LIFE"

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Stormwater detention basins have been utilized for stormwater management for over 40 years. During this time, regulatory and technological changes have made older detention basin designs obsolete. Additionally little is known about the longevity of the physical and biological components of these systems. To gain a better understanding of the potential service life of detention basins this thesis compares conditions at basins built between 1970 and 2011. The study specifically examines soil infiltration rate, the ability of older designs to fulfill new regulatory requirements, the condition of concrete structures, and the diversity of plant communities in Middlesex and Mercer Counties, New Jersey detention basins. Basin age had little effect on the soil infiltration rates. Basins built before 2004 are able to meet their original peak flow reduction standards however overall they cannot meet New Jersey's 2004 peak flow, groundwater recharge, or water quality requirements. Age also had little effect on the condition of concrete structures in the detentions basins and on maintenance concerns such as sediment accumulation. There was a weak negative correlation between basin age and plant diversity. Additionally, plant growth was strongly associated with sediment clogging in inlets. Overall, research suggests that with proper maintenance, after 30 years detention basins can continue to perform their original functions. However new standards may necessitate basin replacement or retrofitting.

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To start off the acknowledgements section, I should first point out that this is all Frank Gallagher's fault. In my first semester as a graduate student I saw him give a really interesting presentation and a month later wound up with the urban forestry group. I have to thank our ringleader and my adviser Jason Grabosky who supported me both financially and morally through this crazy research project. My committee members Dr. Obropta and Dr. Uchrin were also extremely supportive of my work throughout this process. Along the way I got help from a lot of people. The rest of the urban forestry group have been given me a lot of good advice, suggestions and beer. Dr. Gimenez let me borrow two tension infiltrometers for my soils work. Christine Brown of the Water Resources Program taught me how to use the water resources program survey equipment. Dr. Steven Yergeau helped me wade through the Hamilton dataset and found extra data that I needed for my analysis. I could not have found many of my research sites without the help Mike Hill at the Freehold Soil Conservation District. I'm really grateful to my friend Joanna Marino and my undergraduate research assistant Tara Niezthold who were a tremendous help with data collection. And last but certainly not least, thanks to my family and friends for helping me stay sane and still have fun during my time as a graduate student.

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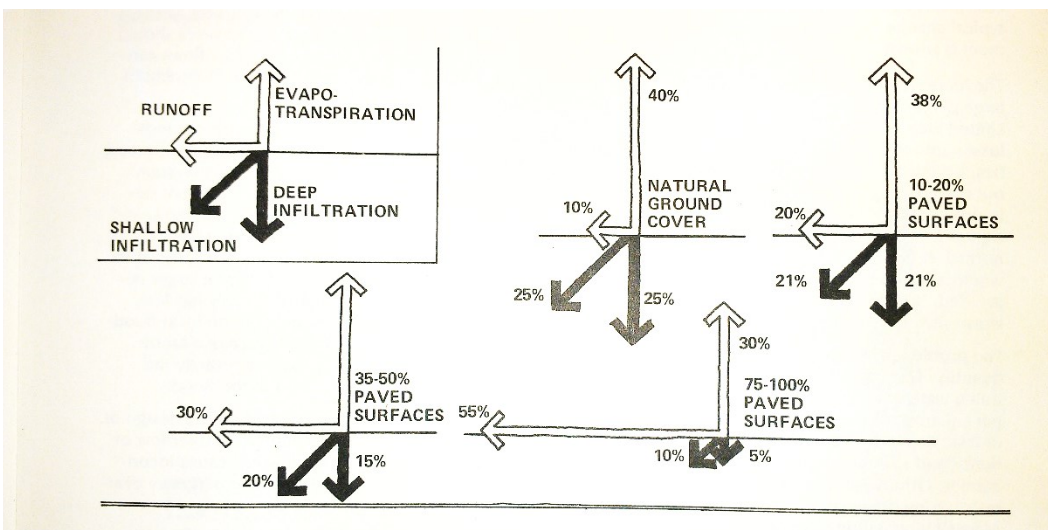
Chapter 1 - Introduction

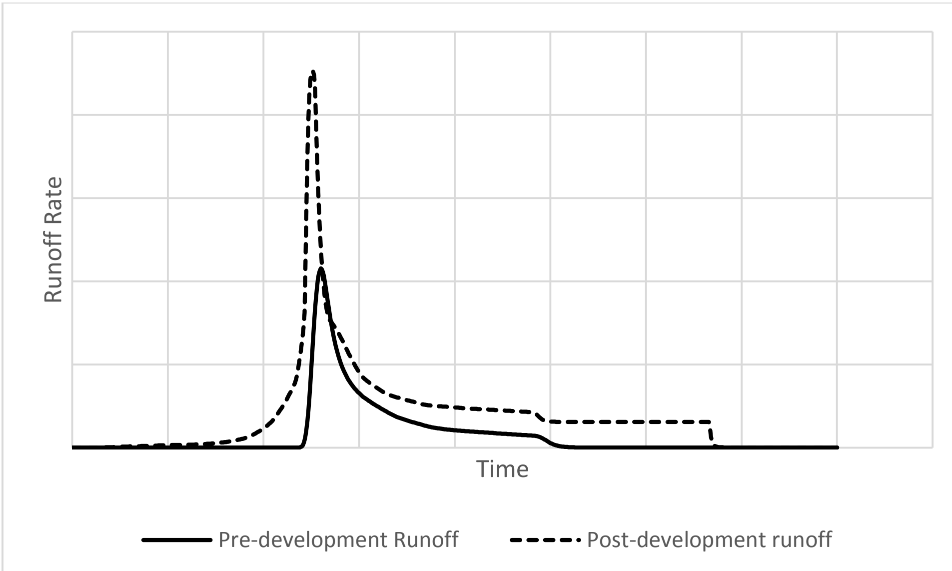
When it rains in a natural environment, one full of plants and soils left undisturbed by human activity, the rainwater can soak into the ground, return to the atmosphere through evapotranspiration, or move over the ground surface as runoff. As Figure 1 shows, with natural ground cover most of the water infiltrates into the soil or is lost through evapotranspiration. The partitioning of water in the hydrologic cycle is much different in a built environment. The addition of paved surfaces and buildings into a landscape reduces the ability of the soil to absorb water so that up to 55% of rainfall can become runoff (Figure 1). The higher volume of runoff generated in the urban environment can cause severe erosion in streams and rivers (McCuen and Moglen, 1988).

Figure 1: Typical changes in hydrologic flows in environments with varying impervious cover. (From Tourbier and Westmacott 1981)



The nature of a landscape also influences the velocity of runoff. Figure 2 is a set of hypothetical hydrographs for a watershed pre- and post-development. The pre-developed scenario produces a much lower peak flow than its developed counterpart; the developed scenario's peak flow also occurs earlier. These characteristics of a built landscape can cause or exacerbate flooding by filling a stream or river with water in a short time frame.

Figure 2: Sample hydrograph comparing pre-development and post-development runoff rates (also referred to as discharge).



As stormwater moves through the built environment is can also entrain and transport pollutants that have collected on impervious surfaces. Nationwide data collected between 2008 and 2012 show that urban related runoff/stormwater was the 6th leading source of impairment for assessed rivers and streams, while ranking 7th for lakes and reservoirs and 11th for bays and estuaries (USEPA 2013). Urban-related runoff/stormwater is the probable source for 51,777 miles of threatened or impaired rivers and streams, 858,171 acres of threatened or impaired lakes and reservoirs, and 1,877 square miles of bays and estuaries (USEPA 2013). In the past three decades, Federal and State water quality regulations have set increasingly stringent standards for stormwater quality in an attempt to address these water quality impairments.

There are many different structural and nonstructural strategies available for reducing the amount of pollutants in stormwater as well as decreasing its speed and volume. This research project focuses on one type of structural stormwater management practice, dry detention basins. Since there is not a standard nomenclature for stormwater management systems (also referred to as stormwater control measurers or best management practices), for the purpose of this study detention basins are defined as manmade depressions in the ground that utilize an outlet structure to temporarily store water and then release it slowly. Additionally there is no (or at least very little) standing water in these systems between storms.

Currently, State of New Jersey Stormwater Management Rules (N.J.A.C. 7:8) require that stormwater management practices must be implemented for development projects disturbing one or more acres of land or increasing impervious surface area by 0.25 acres or more (referred to as major development). The 2004 performance standards for stormwater management at major developments fall into three categories: groundwater recharge, stormwater quantity impacts, and stormwater quality (the specifics of each requirement are further detailed in Chapter 3). These standards replaced the State's 1983 Stormwater Rules which had only required peak flow reduction and less strict quality standards. One problem with stormwater management is that once a detention basin or other structural management practice is installed, they are rarely upgraded as regulations change. An exception is when individual management districts may require retrofitting of older systems, such as in Ocean County, NJ (Ocean County Department of Planning 2013).

The National Research Council (2008) cites uncertainty about the longevity of stormwater control measures as a major shortcoming of the national stormwater program. As further explained in Chapter 4, there is variation in reports of detention basin expected service life, i.e. the amount of time a system can perform its intended functions. Additionally while there are many studies about the pollutant removal capacities of detention basins, there is a lack of multi-decade longitudinal studies of these systems. Table 1 contains a list of research projects on detention basins and related systems and shows the variation in system age at the time of study. Ages range from less than 1 year to 27 years, the median age is 7 years. Unfortunately variations in methodologies and site conditions make the results of these studies difficult to compare and to draw conclusions about long performance. In addition to age related deterioration, maintenance may play an important role in long term performance of systems (Lindsey et al. 1992).

Table 1: Performance studies of detention basins and related stormwater management practices and system age at time of study.

Type of system	Age	Study
Dry detention	18 years	Guo 1997
Dry detention	10 years	Maldonato and Uchrin 1994
Stormwater ponds	3 to 22 years	Bishop et al. 2000a
Wet detention pond	18 months	Farm 2002
Erosion control structures	<1 year	Schuster and Grismer 2004
Bioretention basin	4 years	Emerson and Traver 2008
Dry detention and naturalized basins	13 to 27 years	Hogan and Walbridge 2007
Agricultural best management practices	20 years	Bracmort et al. 2004
Dry detention	4 years	Stanley 1996
Dry detention	7 years	Mallin et al. 2002
Wet detention ponds	14 years	Wu et al. 1996
Wet detention ponds	4 years	Hossain et al. 2005
Wet detention ponds	<1 year	Pettersson 1988
On-stream detention pond	10 years	Van Buren et al. 1997
Detention pond	6 years	Martin 1988

In order to continue meeting goals to improve the quality and health of waterbodies, stormwater management practices need to continue performing their intended functions. In some cases basins may need to perform better than their original design. Dry detention basins have been a popular choice for stormwater management since the 1970s (Neil 1982) and are found throughout urban and suburban landscapes. All other infrastructure has a finite lifespan, it is unreasonable to think detention basins are any different. Understanding how detention basins age and their performance changes over time is necessary for the long term management of stormwater in the built environment.

Recognizing the need for more research on the longevity of detention basins, the aim of this study is to broadly explore different components of detentions basins in regard to their age. Identifying problems and performance shortcomings in older detention basins also holds relevance to the management and design of other stormwater structural management practices such as bioretention basins which also employ vegetation and physical infrastructure (e.g. piping). Since a multi-decade longitudinal project is far outside the scope of this thesis, the study instead employs a strategy of comparing basins of different ages in an attempt to identify age related change. Despite efforts to minimize differences between study basins, a major drawback of this method is the potential for confounding factors to cause greater variation than age. The study involves sub-projects that examine four aspects of dry detention basins and their relation to basin age:

1) Soil infiltration capacity
2) Design
3) Structural components
4) Vegetation

The remainder of Chapter 1 provides background information on the history of detention basin development and related regulations. Chapters 2 through 5 detail each sub-project while Chapter 6 contains the study's conclusions.

BACKGROUND

REGULATORY CONTEXT

Both Federal and State law have been the primary drivers of stormwater management in the United States for the past 40 years. The goals and requirements of these legislations influence the design and implementation of stormwater management practices. The following is an overview of the history of Federal and New Jersey legislation relevant to stormwater.

The 1970s sees the creation of the Environmental Protection Agency (USEPA), a Federal department tasked with handling the growing concerns about pollution throughout the nation. Two years into the agency's existence in 1972, Congress passes what is commonly referred to as the Clean Water Act (its official name is the Federal Water Pollution Control Act Amendments of 1972, P.L. 92-500). The 1972 Act predominately focused on controlling pollutant discharge from point sources, such as industrial facilities, through a permitting process. In this version, the Act addresses stormwater and nonpoint source pollution as subjects in need of further study and investigation. Congress amended the Clean Water Act in 1977 (P.L. 95-217) though none of the changes affect the national policy on stormwater and nonpoint source pollution.

Meanwhile, the New Jersey State Legislature passed the New Jersey Stormwater Management Act in 1981 (P.L. 1981 c. 32) which required every municipality in the State to incorporate storm water management plans and control ordinances into their municipal master plans. The primary motivation behind the 1981 Stormwater Management Act is to address issues stemming from flooding (Assembly Municipal Government Committee 1980).

The New Jersey Department of Environmental Protection (NJDEP) adopted Stormwater Management Rules in 1983 which required municipalities to develop stormwater management plans in a two phase process. In the first phase, the municipality would develop an ordinance that would require new development sites to employ strategies to keep a site's peak runoff at the same level or less than pre-construction runoff. It should be noted that this is not equivalent to reducing a site's total stormwater volume to pre-development levels; it only affects the timing of the water's release. The rules also have requirements for detention times to address water quality issues; specifically a residential site needed to be able to detain then release 90% of a design storm over the course of 18 hours in a residential development and 36 hours in all other cases.

The U.S. Congress amended the Clean Water Act again in 1987 (P.L. 100-4), this time with several major additions affecting stormwater management. One amendment, Section 319, makes nonpoint source pollution management the responsibility of individual states which have to identify water impaired by nonpoint source pollution, the sources of the problems, and reduce the pollution to the maximum extent practicable. Another major amendment to the Clean Water Act was Section 405 which expanded the scope of the National Pollutant Discharge Elimination System (NPDES) to require most industries, construction sites, and municipalities to obtain permits for stormwater discharges. NPDES was originally designed to reduce the concentration of pollutants discharged from point sources. Though runoff is characterized as a nonpoint source of pollution, Congress was able to include it under NPDES by classing stormwater outfall pipes as point sources of pollution.

New Jersey's stormwater management rules received their first major rewrite in over decade in 2004. The 2004 performance standards for stormwater management at major developments fall into three categories: groundwater recharge, stormwater quantity impacts, and stormwater quality. Groundwater recharge at a post-construction site should either be the same as the average annual pre-construction volume or a site should be able to infiltrate the post-construction volume generated by a two-year storm. There are three design standard choices for handling the quantity of stormwater runoff: demonstrate that the pre- and post-construction hydrographs for a site are the same; demonstrate that peak runoff rates remain unchanged providing the changes in volume or timing do not exacerbate flooding; or design measures that allow post-construction peak runoff rates to be certain percentages of various design storms. Quality standards cover total suspended solid (TSS) reduction, which should be 80% of the expected load, and nutrients. The nutrient standard requires measures to reduce nutrients to the maximum extent feasible, though addressing nutrients should not interfere with the recharge, quantity, and TSS standards. New Jersey's stormwater rules remain unchanged since the 2004 rewrite and its expiration date has been extended three times since 2009.

HISTORY OF STORMWATER MANAGEMENT AND DETENTION BASINS

The design of stormwater detention basins built in the 1970s and 1980s differ markedly from those built in the 1990s and 2000s because of changes in the technological and regulatory landscapes. These differences have important implications in the comparison of older and younger basins.

In the post-World War II construction boom, the goal of stormwater management was to prevent local, or nuisance flooding – keeping water from ponding on roadways and private property (NRC 2008). The prerogative of these standards was to control and convey stormwater away from development in a timely manner (Calkins 1970). However the efforts to treat nuisance flooding resulted in larger scale flooding further downstream. Consequently the focus of stormwater management shifted towards reducing flooding by managing peak flow (Jens 1975). One of the most common methods to manage peak flow was to temporarily detain stormwater in order to make the height of the post-development hydrograph match that of the pre-development graph (Figure 2). The technique is also referred to as peak flow attenuation or peak shaving. The outlet of a detention system is smaller than its inlet, this restricts the flow of water out of the basin, effectively serving as a speed bump for stormwater.

A 1981 report by the American Public Works Association found that flood control was a very high priority for many municipalities; much of the report focused on the implementation of onsite detention facilities for the management of excess runoff (Neil 1982). As an example, solutions to flooding in a set of Kentucky towns included the installation of detention basins, floodwalls, and the widening of drainage ditches (Hemming 1976). Hemming points out that these projects were all reactive, indicating a lack of centralized planning in stormwater management. McCuen (1979) also documents the popularity of stormwater management basins for flood control, but argues that a lack of volume control and regional planning limit the effectiveness of these systems for protecting the integrity of downstream waterbodies. Thirty years later volume control and regional planning continue to be challenges for stormwater management (NRC 2008).

An interest in stormwater and water quality in the United States began as early as the 1950s. In earlier efforts to convey stormwater out of developed areas, many cities created combined sewers by diverting stormwater into sanitary sewers. The result of this practice was the discharge of untreated sewage into waterways during heavy rains when the high volume of stormwater overwhelmed wastewater treatment facilities (Dunbar 1966). Initial studies of combined sewer overflows (CSOs) focused on biological oxygen demand, suspended solids, and coliform bacteria, the same pollutants of interest to wastewater management (Palmer 1950, Dunbar 1966). Potential treatment options included temporary storage facilities, disinfection through chlorination, settling, and the separation of sewer systems (Palmer 1950, Dunbar 1996). By 1976, many cities were developing solutions to manage CSOs through sewer separation, the creation of detention tanks, and improved wastewater treatment methods (Field et al. 1976).

Combined sewers continue to pose water quality problems in major metropolitan areas such as Kansas City, Missouri and New York City. New York City anticipates spending over $2 billion on “green” infrastructure to reduce the frequency of overflow events in its five boroughs (Landers 2012). Kansas City is in the process of implementing a 10,000 Rain Gardens program which uses bioretention basins to reduce the volume of stormwater in the area to prevent overloading the system. In a life-cycle cost study, Cohen et al. (2012) calculated that a program installing 51,822 rain gardens along with 38,000 feet of additional piping would save $35 million compared to a strategy that only used piping to increase system capacity. Interestingly, detention basins do not play a large role in either of these ambitious plans.

The stormwater collected by separate sewers was also the subject of research on water pollution in the 1960s (Dunbar and Henry 1966**,** Evans et al. 1968). Evans et al. (1968) suggested that as wastewater treatment is improved and implemented, urban runoff may be the next important source of water pollution to address. The United States Public Health Service and the American Society of Civil Engineers also identified urban runoff as a potentially serious threat to water quality (USEPA 1983).

In order to develop a consistent data set about urban runoff to inform future stormwater management and planning decisions, USEPA began the National Urban Runoff Program (USEPA 1983) in 1978. Five years later, USEPA released the results of the NURP, a set of studies characterizing urban runoff at 28 projects across the United States. While the individual projects were run by local agencies, they were coordinated by EPA in order to develop a consistent data set that could be used to inform future stormwater management and planning decisions. Using event mean concentration (EMC) as its primary metric for contaminants, NURP found high variability in stormwater pollutant concentrations. An EMC is the total mass of a particular pollutant produced by a single runoff event divided by the volume of runoff produced by the event. EMCs for various contaminants varied from event to event and site to site; EMCs for each pollutant tend to be log normally distributed. Out of the EPA's priority pollutant list, copper, lead and zinc were the most prevalent heavy metals found in the studies, often at levels surpassing ambient water quality criteria. Coliform bacteria counts were high, often violating fecal coliform standards, while nutrient levels were generally an order of magnitude less than those from treated wastewater discharges. Total suspended solid concentrations were also comparatively high compared to treatment plant outflow and also tended to have other pollutants, such as heavy metals, adsorbed onto sediment particles.

Detention basins were one method used to enhance stormwater quality before it could reach receiving waters due to their ability to promote sedimentation (Randall 1982). Stormwater managers in the Oceoquan Watershed in Virginia implemented a system of detention ponds for water quality improvement in order to protect a downstream reservoir from new suburban development. It was also recognized that wet basins had the ability to provide some biological treatment in aerobic conditions (Smith 1982). Disinfection was proposed as a means of treating stormwater for pathogens (Smith 1982), however this treatment method never caught on. A review of research by Field and Cibik (1980) describes several pilot projects that attempt to treat pollution in stormwater using wastewater treatment methods. The difficulty faced by these treatment methods was the extreme temporal variability of pollutants in stormwater.

One of the challenges of incorporating water quality improvement into earlier stormwater management strategies was that basins built for flood control and peak flow reduction were designed based on storm events with large recurrence intervals, usually 10 years or greater (Bell and Kar 1969). However, smaller, frequent storms are a greater source of stormwater pollution. One solution for treating water quality and quantity issues was the creation of dual purpose basins that are configured to detain both small and large storm events (Ormbsee, et al. 1987; Kropp 1982). Most commonly, dual purpose basins utilize an outlet structure with multiple orifices (Figure 3). A small, lower orifice provides detention for small storms to improve water quality while a larger, higher orifice provides peak flow control for larger storms. Herein lies a crucial difference between older and younger basin. When evaluating basin conditions and performance, one must first ask the question if the basin was designed solely for flood control, or water quality as well?

Figure 3: Example of a dual purpose outlet with multiple orifices to control both small and large storm events.

NURP projects also evaluated the performance of detention devices and other stormwater treatment systems; detention was the most commonly used treatment strategy. NURP concluded that properly designed wet detention basins had the greatest capacity for treatment while dry detention basins designed for peak flow reduction had the worst. However dual purpose basins (designed to treat peak flow and provide pollutant removal) provided adequate pollutant removal as well. In New Jersey 2004 Stormwater Rules, out of eight options, detention basins offer the lowest TSS removal rate.

Through the use of regulatory requirements, detention basins and other stormwater management systems proliferated through the landscape as land was developed in the 1980s and 1990s. However even with all these rules, streams, lakes, and rivers continued to experience problems with pollutant loading and flooding. A new school of thought called Low Impact Development (LID) sought to address these persistent issues by proposing a different set of strategies for managing stormwater (Davis et al. 2009). While the traditional stormwater management sought to control the excessive runoff generated by the urban environment, LID proposes creating an urban hydrologic cycle that mimics a natural one. Many LID techniques aim to promote infiltration of stormwater and to utilize diffuse, smaller scale systems. Bioretention basins are an example LID technique which utilize plants, soil, and infiltration to reduce pollutants and stormwater volume.

While the field of stormwater management continues to advance, older and more traditional stormwater management systems continue to be a part of the landscape and continue to be installed at new development sites. Chapter 5 describes several techniques for retrofitting existing detention basins to enhance their pollutant removal performance which provides a solution to issue of obsolete systems.

The history of detention basin development suggests several reasons why dry basins have been a popular management technique and may be informative for the development of future stormwater control measures. The first is regulatory preference and prioritization of peak flow reduction at which detention basins excel. This demonstrates the strong influence of legislation on management practice selection. Secondly, as a passive treatment system detention basins require very little attention from property owners. Early on, active wastewater treatment style systems were proposed and tested but never caught on, presumably because of the higher demands of operating such a system. Thirdly, detention basins are far less prone to clogging issues compared to LID systems which utilize infiltration to reduce volume. Despite these advantages, because of their mediocre water quality treatment performance, the use of detention basins may phase out in the future if regulatory priorities continue to emphasize pollutant removal and volume control.

Chapter 2: Soil infiltration rates in stormwater detention basins after 10 to 30 years of use

INTRODUCTION

In addition to managing peak flow and reducing pollutant loads, stormwater management practices are now also expected to recharge groundwater. Maintaining groundwater levels is important for maintaining the base flow of streams and rivers in dry weather. Groundwater is also the sole water supply resource for many communities. Buildings, roads, and the compaction of soil during the construction process disconnect water on the land surface from shallow and deep aquifers (USEPA 2012a). To offset this loss of pervious land, a common technique involves creating a temporary storage facility for stormwater where it can have time to soak into the ground instead of becoming surface water. Infiltration basins, infiltration trenches, bioretention basins (rain gardens), porous pavement, grassed swales, and sand filters are commonly used stormwater infiltration systems (USEPA 2012b).

In the 2004 update to its stormwater regulations, the State of New Jersey incorporated groundwater recharge into the new rules. Major development (disturbing one or more acres of land or increasing impervious area by 0.25 or more acres) must fulfill one of two recharge requirements if site conditions permit. The first option involves determining the average volume of groundwater recharged at a site before it is developed, then implementing strategies that will infiltrate that same volume on a yearly basis after development. The second option involves calculating the difference between the volumes of stormwater generated by a two-year design storm before and after development, then designing strategies which can infiltrate that volume of stormwater. Projects can be exempted from the groundwater recharge criteria if they are located in an industrial zone or are sited on a soil with low permeability (USDA hydrologic soil group C or D).

A common problem with infiltration systems is their potential for clogging, meaning water can no longer flow through the soil with ease. As stormwater ponds on top of an infiltration bed, the sediment carried by and suspended in the water tends to collect on the surface of the soil which can create a clogging layer that decreases hydraulic performance (Hatt et al. 2007). One manual for stormwater management practitioners points out that the accumulation of excessive sediment can result in the failure of an infiltration BMP, meaning stormwater will be ponded for prolonged periods of time (potentially creating a breeding habitat for mosquitoes) and the system can overflow (Livingston et al. 1997).

A survey of stormwater infiltration systems in Maryland found half of the 177 study sites were not functioning as designed, meaning 72 hours after a storm the sites had not drained completely as intended. Inspections by stormwater professionals found 33% of the sites had clogging while 42% had buildup of excessive sediment or debris (Lindsey et al. 1992). However Hilding (2000) suggests that infiltration basins constructed on sandy soils are less prone to clogging; after 10 years of operation 23 infiltration basins surveyed in Puget Sound maintained an mean infiltration rate of 15.8 in./hr (range 1.1 to 36 in./hr). In a study of two infiltration trenches in an urban area, the saturated hydraulic conductivity of the soil decreased 70% after 2.75 years of operation (Warnaars et al. 1999). Similarly in a laboratory bench study using soil columns and synthetic stormwater containing 115 mg/L of total suspended solids, the median hydraulic conductivity of the samples dropped from 186 mm/hr to 51 mm/hr over the course of 72 weeks. The size of the catchment area relative to the size of the treatment system and the initial TSS loading rates strongly influence the severity of clogging (Emerson et al. 2010). The use of a forebay at the system's inlet to capture sediment before it reaches the infiltration bed can prolong the onset of clogging (Livingston et al. 1997). However, an EPA operations manual for stormwater BMPs does not offer an estimate of how long a forebay could extend the functionality of an infiltration system. This highlights the lack of research on BMP longevity.

Detention basins can be designed to infiltrate some stormwater, often through the inclusion of a sand bed or the creation of longer detention times during low flow events to promote infiltration (Rupp 2009, Blick et al. 2005, Larry Walker Assoc. 2006). In some situations, it may not be feasible to infiltrate all of the water generated by a storm event. The advantage of incorporating infiltration into a detention basin is that the system could manage very large flows and recharge groundwater at the same time, instead of performing only one function or the other. It would be useful to understand the infiltration capacity of detention basins which have been in operation for over a decade to further inform the design and maintenance of future infiltration and detention systems. Additionally, if these detention basins are infiltrating stormwater, they may be providing additional environmental services beyond their original design.

Given the prevalence of stormwater detention basins built in central New Jersey before the 2004 rules, what role do these systems play in recharging groundwater? The goals of this study are to:

1) Determine how much water existing detention basins may infiltrate despite not being designed for that purpose.

2) Compare the infiltration ability of sites of different ages as a proxy for studying the condition of detention basin soil over several decades.

SOIL METHODS

Site Location

Ten detention basins in Middlesex County, New Jersey were selected for this study due to their range of installation years and ease of access. All of the basins are a part of residential complexes or commercial developments with the exception of NE01 which is located in a park, though it receives a portion of its inflow from a nearby residential site. Table 1 lists the ten sites along with their land use and soil settings. The soil series assigned to each site were based on the Natural Resource Conservation Service's online soil mapping program, Web Soil Survey (2013). Typical profiles for each type of soil are described in Appendix A.

Table 1: Detention basin characteristics. Typical depth profiles for each soil type can be found in Appendix A.

Site	Installation Year	Basin Area (acres)	Catchment Area (acres)	Basin Depth (ft)	Soil Type	Land Use
ED02A	1993	0.565	7.189	6.0	Lansdowne silt loam	High Density Residential
ED02B	1993	0.416	7.292	8.0	Klinesville channery loam	High Density Residential
ED09	1982	1.768	28.217	8.0	Nixon loam	College Campus
ED10	1984	0.095	6.490	5.5	Nixon-Urban land complex	Commercial
NE01	1996	0.584	unknown	7.5	Reaville silt loam	Residential
NO01	1993	1.356	30.795	9.0	Elkton loam	High Density Residential
PI03	2004	0.475	Unknown	7.5	Parsippany silt loam	High Density Residential
PI05	2004	0.497	8.459	6.5	Parsippany silt loam	High Density Residential
PI06	2004	0.755	5.914	8.0	Lansdowne silt loam	High Density Residential
PI07	2004	0.513	10.246	7.0	Lansdowne silt loam	High Density Residential

With the exception of NE01 which contains a variety of forbes, all of the detention basins are covered with turf. PI03, PI05, PI06, and PI07 additionally contain nursery grown trees. PI03 has the largest tree, a *Salix babylonica* with a diameter at breast height (DBH) of 11.8 inches. The DBH of trees in the other basins range from 2 to 5 in. Plant growth in detention basins is more thoroughly documented in Chapter 5.

Site selection also accounted for underlying geology and soil formations in an effort to minimize confounding differences, though it was not possible to find or access enough sites on a single type of soil to have complete uniformity. Figures 1 through 3 show the location of the sites and their soil, bedrock, and surficial geology settings. The Klinesville, Reaville, Parsipanny, and Lansdowne soils form within the Piedmont physiographic province on mudstone, siltstone, and shale. The profiles of Parsippany and Lansdowne soils are dominated by glacial deposits. The Nixon and Elkton soils are located along the transition zone between the Piedmont and Coastal Plain physiographic provinces. The Nixon series is characterized by both shale and sand parent material while the Elkton soils have a higher clay content (Tedrow 1986).

Figure 1: Soil series and hydrologic soil group (HSG) of detention basin infiltration study sites.

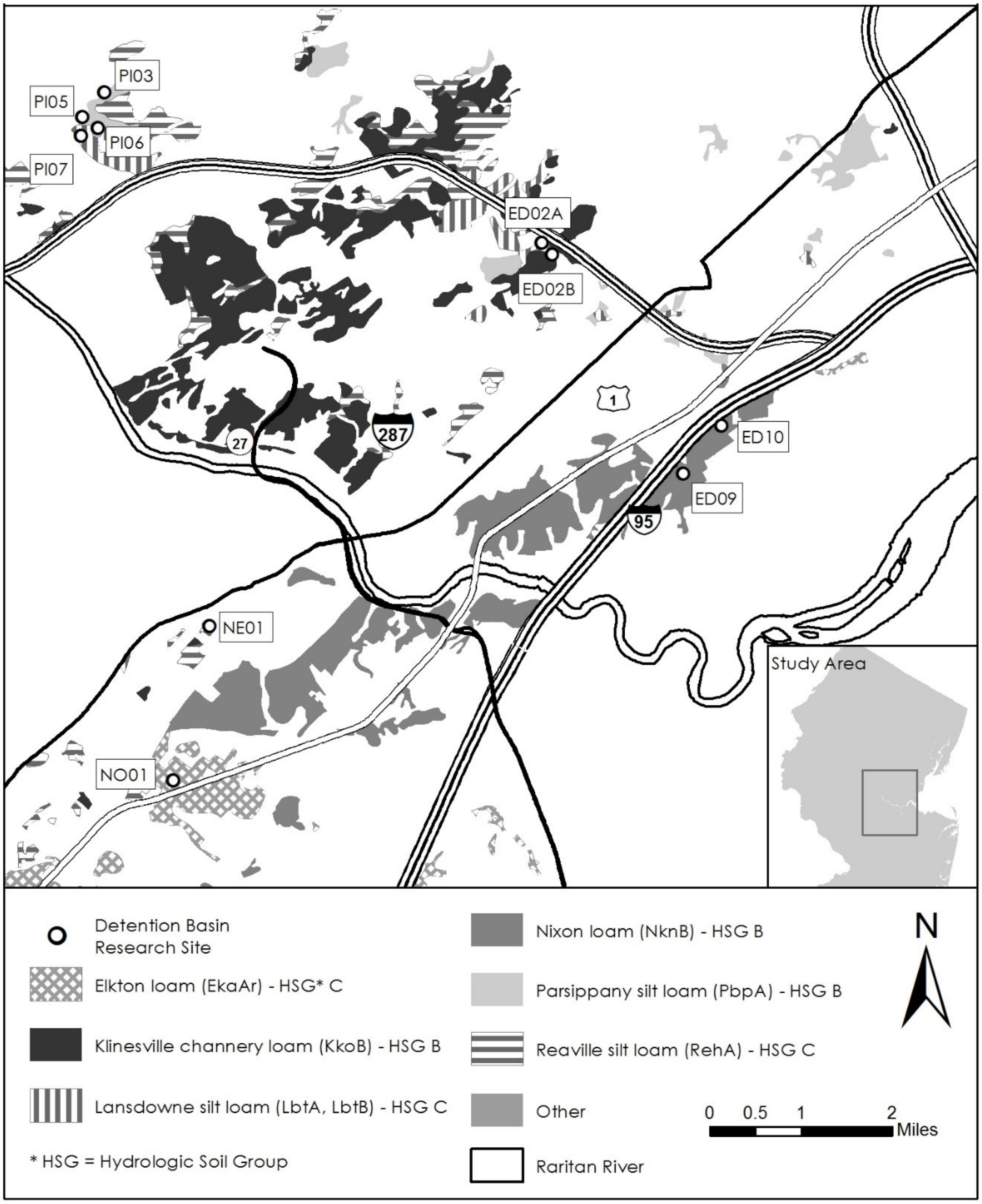


Figure 2: Bedrock geology of detention basin infiltration study sites.

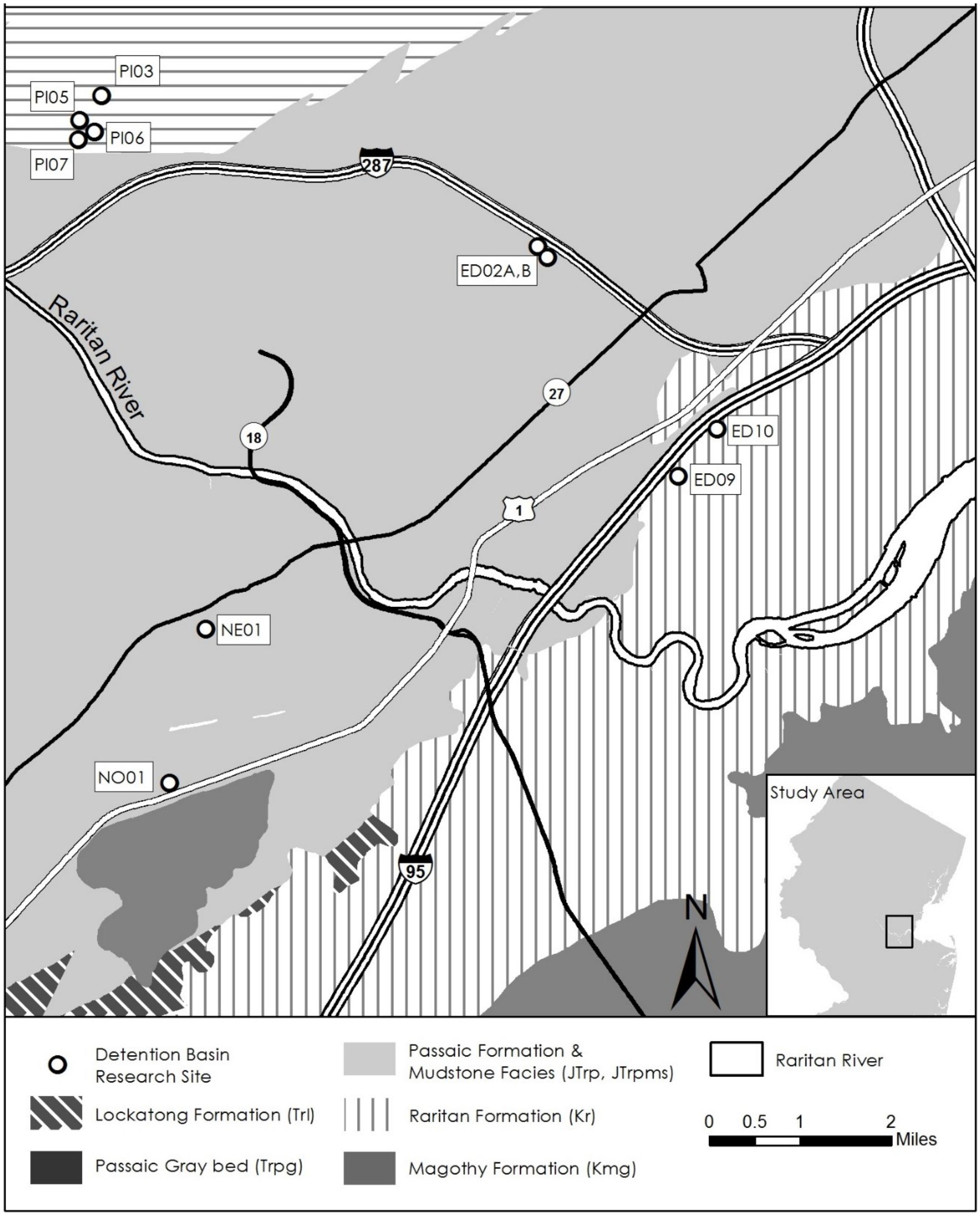
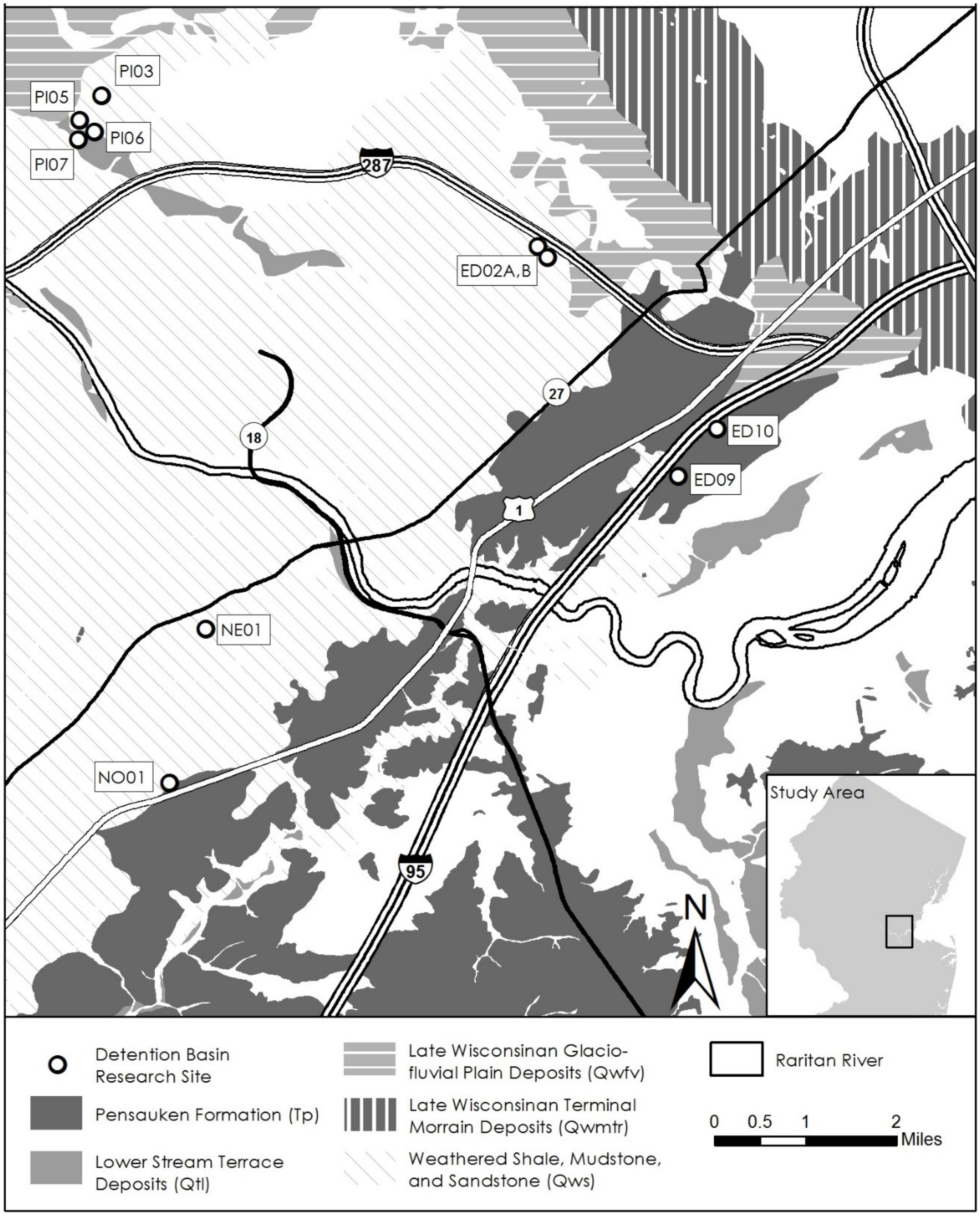


Figure 3: Surficial geology of detention basin infiltration study sites.



In Situ Measurement of Saturated Hydraulic Conductivity

The movement of water through porous media is governed by hydraulic conductivity and the gradient of potential energy of the system. Hydraulic conductivity (K) is a value that represents the ease at which water can move through porous material. The value of K is influenced by properties of the media, in this case soil, and of the liquid. Its units are length over time, similar to velocity. Quantifying the K of a soil is necessary to determine its ability to infiltrate water.

When soil is saturated, meaning all of its void spaces are filled with water, its hydraulic conductivity is constant and referred to as K_{sat}. In reality, it is often impossible to completely saturate a soil in the field so the term field saturation is employed to represent that a soil is effectively saturated. For the purposes of this study, K_{sat} will represent effective saturation in the field. When a soil is unsaturated and its void spaces contain both air and water, the hydraulic conductivity will vary as a function of the pore water pressure head (Ψ) of the soil. Negative pressure head in a soil means water will move into the soil; the soil exerts a pull on water the same way a paper towel or sponge can pull water against the force of gravity. Water moves more slowly through an unsaturated soil as compared to the same soil in a completely saturated state. Unsaturated hydraulic conductivity is represented as K(Ψ) since K varies with Ψ; as Ψ approaches zero, K approaches K_{sat} (Hillel 2004). This study uses the K_{sat} to represent the infiltration rate of the basin since it is reasonable to assume that the soil will be completely, or near completely, saturated when the basin fills with water.

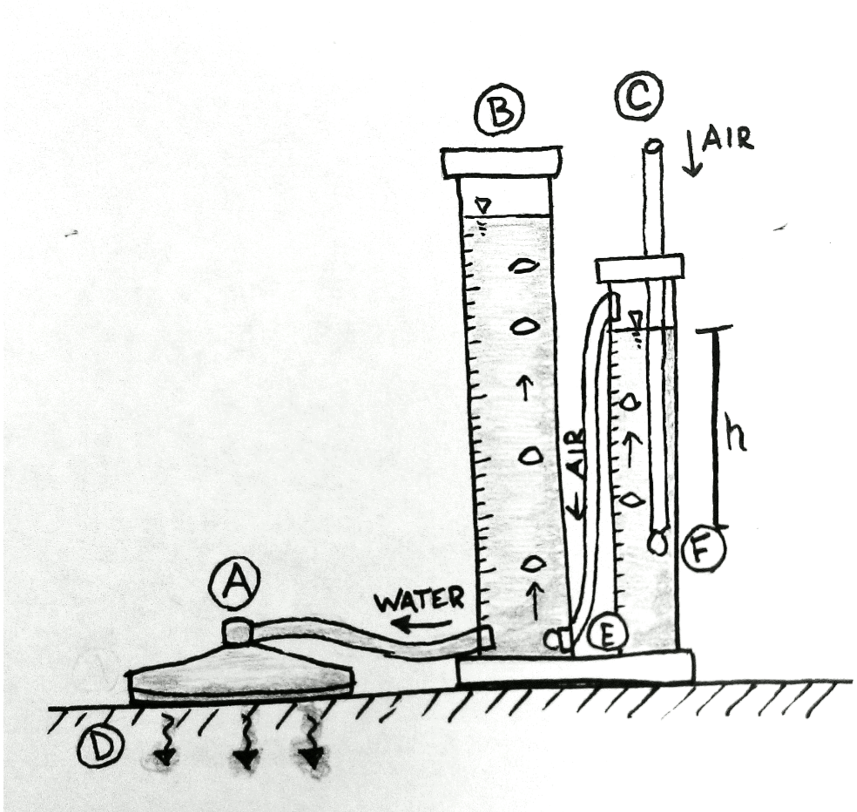
However, K_{sat} is challenging to measure in the field because the presence of air bubbles in the soil and the instability of macropores can alter results. Additionally methods that measure saturated flow, such as single ring infiltrometers, assume that the water flowing out of the equipment and through the soil is only moving in one direction. Since this water is influenced by the capillarity of the soil in addition to gravity, the assumption is inaccurate. By only measuring the capillary flow, a tension infiltrometer provides a more accurate measurement of unsaturated hydraulic conductivity which in turn can be used to calculate K_{sat} (Reynolds 1993). Another advantage of using *in situ* measurements of hydraulic conductivity is the greater likelihood of preserving the structure of the soil when compared to samples removed and transported for laboratory measurements (Reynolds 1993).

While there are several different techniques for using tension infiltrometers to measure K(Ψ), Hussen and Warrick (1993) found that they all produce comparable results at all but 0mm tension. They recommended using a method that used a single large disc to measure infiltration at several different tensions because it is accurate, stable, and repeatable.

A disc tension infiltrometer infiltrates water into the ground under negative pressure, or suction, which creates steady-state unsaturated flow through soil. The tension infiltrometer has three parts shown in Figure 4. The porous disc (A) serves as the interface between the soil and the infiltrometer. Its base is covered with a nylon membrane. The reservoir tower (B) supplies water to the disc for infiltration into the soil. The reservoir tower is marked from top to bottom in 1 mm increments. During an experiment the top of the reservoir is sealed shut. A piece of flexible tubing connects the reservoir tower to the bubble tower (C). The bubble tower controls the amount of suction in the infiltrometer. A rigid plastic straw inserted in the top of the bubble tower is the only way air can enter the equipment. The depth of water, h, between the surface of the water in the bubble tower and the bottom of the straw is the suction of the system and can be adjusted by moving the straw up or down. In order to measure unsaturated flow at a matric potential of -15 cm in the soil, the straw is set -19 cm (15 cm plus a 4 cm adjustment factor) below the water surface in the bubble tower.

Figure 4: Disc tension infiltrometer diagram.

Note: Infiltrometer parts include: porous disc (A), reservoir tower (B), bubble tower and rigid straw (C). Dry soil pulls water out of porous disc (D), air enters the reservoir tower through tube E, and system tension is controlled by the depth of straw F.



The arrows in Figure 4 show the movement of water and air through the infiltrometer. The soil is drier than the infiltrometer disc, so the soil effectively pulls water out of the disc (D) and the adjacent reservoir. The reservoir needs air to replace the water it is losing; since the top of the reservoir is sealed shut, the only way air can get into the reservoir is through the bubble tower (E). To get air into the bubble tower, the matric potential, or pull, of the soil has to be strong enough to overcome the depth of water covering the straw (F).

Tension Infiltrometer Procedure

A tension infiltrometer with a 20 cm diameter disc (Soilmoisture Equipment Corp. Model 2826D20) was used to measure unsaturated hydraulic conductivity of the soil in the bottom of the ten study basins. Measurements were made in randomized locations near the center of the basin where the ground was relatively flat. Ideally, three infiltration measurements would have been made in each basin. However time and equipment constraints resulted in some basins only having one or two measurements instead of three as shown in Table 2 in the Results section.

Before the disc was placed on the ground, the soil was prepared by first cutting all vegetation to be flush with the soil surface. A 20 cm diameter metal ring was placed on the spot and filled with native soil sieved through a 2 mm sieve. The sieved soil was leveled off to ensure a uniform contact surface with the plastic disc; the metal ring was removed before starting the measurements. The rate of water flowing out of the infiltrometer was measured by using a stopwatch to time the drop in water level inside of the reservoir tower. Measurements were made at three to four different suctions with the lowest suction measured first so the last suction would be close to zero, or saturation. The rate of flow at each suction was recorded for 15 to 40 minutes depending on the amount of time needed for the water level to drop consistently, indicating steady state flow.

Calculating Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_{sat}) can be calculated from measurements of unsaturated hydraulic conductivity made at two or more tensions based on equations from Gardner (1958) and Wooding (1968), (see Hussen and Warrick 1993). Wooding approximated steady state infiltration into unconfined soil from a circular source with the following equation:

$$Q = \pi r_o^2 K \left[1 + \frac{4}{\pi r_o \alpha}\right] \quad (1)$$

Where Q is the steady state infiltration rate (in.^{3}/hr), r_o is the radius of the infiltrometer disc (L), K is hydraulic conductivity (in./hr), and α (1/in.) is a constant also used in Gardner's equation. Gardner's equation describes the relationship between the unsaturated hydraulic conductivity of a soil and its matric potential at any given time:

$$K(h) = K_{sat} \exp(\alpha h) \quad (2)$$

Where K(h) is unsaturated hydraulic conductivity (in./hr) at matric potential h (in.), and K_{sat} is saturated hydraulic conductivity (in./hr). Equations 1 and 2 can be combined together for two separate values of h:

$$Q(h_1) = \pi r_o^2 K_{sat} \exp(\alpha h_1) \left[1 + \frac{4}{\pi r_o \alpha}\right] \quad (3)$$

$$Q(h_2) = \pi r_o^2 K_{sat} \exp(\alpha h_2) \left[1 + \frac{4}{\pi r_o \alpha}\right] \quad (4)$$

Equations 3 and 4 can be combined together to solve for α:

$$\alpha = \frac{\ln[Q(h_2)/Q(h_1)]}{h_2 - h_1} \quad (5)$$

Note that h_1 is greater than h_2. Once α is calculated, it is used in equation 3 or 4 to solve for K_{sat}.

A major drawback of this approach is that it is a linear approximation of the exponential relationship between hydraulic conductivity and matric potential (Šimůnek and vanGenuchten 1996). One way to address this issue is to make measurements at more than two tensions. By calculating K_{sat} for tensions that are closer together, the relationship is more linear thus improving the approximation.

RESULTS

Table 2 shows the saturated hydraulic conductivity (K_{sat}) for the bottom of the ten detention basins calculated from the tension infiltrometer measurements. Site PI05 had the lowest K_{sat} of all the sites at 0.07 in./hr while one of ED02B's measurements produced the highest K_{sat}, 240 in./hr. The other two measurements made at ED02B produced significantly lower K_{sat} values, 0.99 and 1.31 in./hr; additionally the K_{sat} at the second basin at this site, ED02A, ranged from 0.24 to 0.36 in./hr. This suggests that the 240 in./hr measurement at ED02B is an outlier measurement, possibly caused by a large macropore or poor setup of the instrument; consequently this measurement was excluded from further analysis in the study. One test at Site NE01 also produced a high K_{sat}, 37.56 in./hr, while the second test was only 2.19 in./hr. NE01 was the only site in the study with non-turf vegetation, the bottom of the basin was colonized by grasses, sedges, and forbes. The high K_{sat} may be attributed to macropores created by more extensive root growth.

An unbalanced one-way Analysis of Variance (ANOVA) was used to test the null hypothesis that K_{sat} does not vary based on the age of the detention basin (Oehlert 2010). Significance was determined at the five percent level ($p<0.05$). Measurements were grouped based on the decade of installation: 1980s, 1990s, and 2000s. In order to satisfy the assumptions of normality and constant variance for ANOVA, the data were transformed with a natural logarithm (log_e). The ANOVA did not disprove the null hypothesis (p=0.394); there was little variation between age groups as shown in Figure 5.

Table 2: Saturated hydraulic conductivity (Ksat) at study sites.

Site	Installation Year	Sample Date	Ksat (in./hr)
ED09	1982	10/23/12	0.19
ED09	1982	10/23/12	0.29
ED10	1984	10/17/12	0.14
ED10	1984	10/17/12	0.95
ED02A	1993	8/21/12	0.24
ED02A	1993	8/23/12	0.28
ED02A	1993	10/8/12	0.36
ED02B	1993	10/1/12	0.99
ED02B	1993	9/26/12	1.31
ED02B	1993	9/26/12	240.42
NO01	1993	10/9/12	0.09
NO01	1993	10/11/12	1.76
NO01	1993	10/11/12	2.86
NE01	1996	7/31/12	2.19
NE01	1996	7/31/12	37.56
PI03	2004	8/16/12	0.13
PI03	2004	8/16/12	0.40
PI03	2004	8/20/12	2.36
PI05	2004	8/8/12	0.07
PI05	2004	8/8/12	0.07
PI06	2004	8/13/12	0.09
PI06	2004	8/13/12	0.88
PI07	2004	8/12/12	0.57

Table 3 and Figure 6 compares the reported range of K_{sat} for the most restrictive layer of the soil series to the measured K_{sat} at each site. The sites installed in the 1980s on Nixon loam/Nixon Urban Land Complex (NknB/NkpB) were the only ones to have measured K_{sat} be less than the reported values. All the K_{sat} values for the 1993 sites installed on Lansdowne silt loam (LbtB) were higher than reported values. The remainder of the measurements were within or slightly over the reported range for their respective soils.

Figure 5: Boxplot of the natural log of saturated hydraulic conductivity (K_{sat}) at each site, grouped by decade.

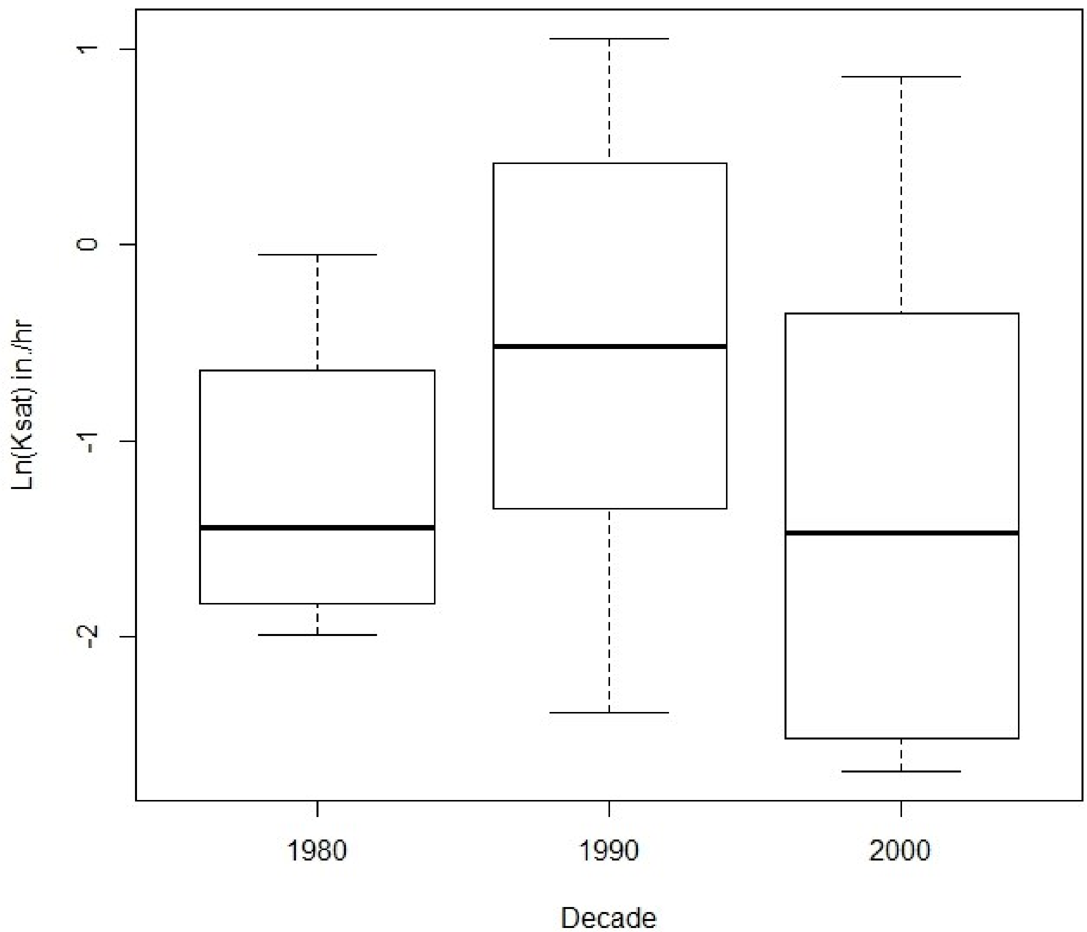
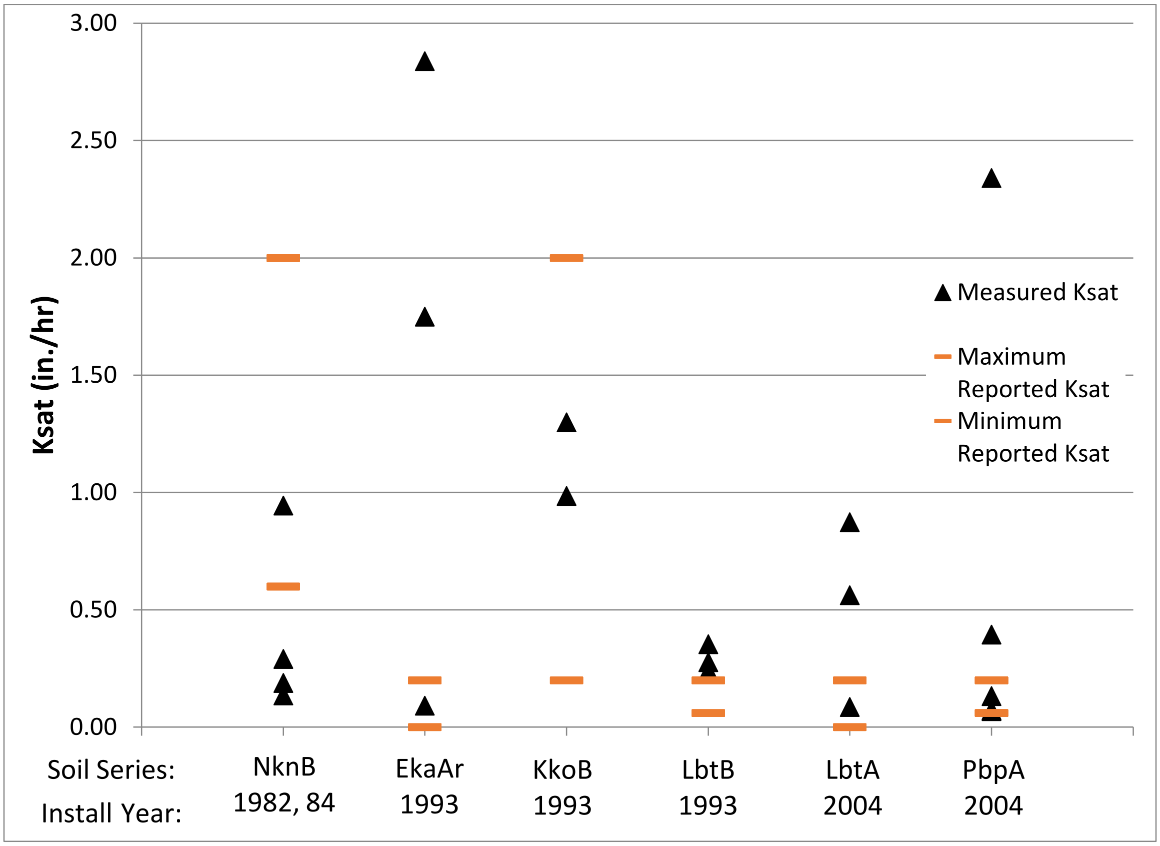


Table 3: Reported minimum and maximum saturated hydraulic conductivity (K_{sat}) for the most restrictive layer of each soil series at study sites (NRCS 2012).

Soil Code and Series Name	Reported Min. Ksat (in./hr)	Reported Max. Ksat (in./hr)
EkaAr - Elkton loam	0	0.2
LbtA - Lansdowne silt loam	0	0.2
LBtB - Lansdowne silt loam	0.06	0.2
PbpA - Parsippany silt loam	0.06	0.2
KkoB - Klinesville channery loam	0.2	2
NknB - Nixon loam	0.6	2

Figure 6: Measured and Minimum, Maximum Reported Ksat by soil type.



DISCUSSION

This study adopted a strategy of trading space for time in order to examine how the ability of a detention basin to infiltrate water could change over the course of several decades. There was an expectation that after many years of use, the buildup of a layer of sediment on the bottom of the basin would reduce the hydraulic conductivity (K_{sat}) of the basin's soil. The K_{sat} of the study sites built in the 2000s were expected to be higher than those built in the 1980s. However, as shown in Figure 5 this was not the case.

Table 3 provides the range of K_{sat} for the most restrictive layer of each of the soil series found at the study sites. ED09 and ED10, the two oldest sites in the study, are both located on Nixon soils which form on the transition between the Piedmont and Coastal Plain physiographic provinces. Consequently, the composition of the Nixon series is highly variable, being dominated by sand in some areas or a red shale in others (Tedrow 1986). While ED09 and ED10's measurements are lower than their expected values the difference is small, on the same order of magnitude as the minimum reported Nixon K_{sat}. This is not strong enough evidence to support the idea that age is responsible for a clogging layer when the low K_{sat} could also be attributed to variation in the Nixon soil series.

Two of the measurements made at NO01 produced infiltration rates 10 times higher than the rate reported for Elkton Soils. This series forms in low lying areas, often with hardwood swamps, and is also located on the transition between the Piedmont and Coast Plain physiographic provinces. The C horizon in a typical Elkton profile begins about 3 feet deep and can grade into sand and gravel which would have a higher conductivity than the silty clay layers above. Higher measured infiltration rates could be attributed to the basin being excavated into the lower, more conductive layers of the soil profile.

With the exception of one outlier, the infiltration rates at ED02B were both within the reported range. The Klinesville series is a shallow variant of the Penn, which forms a silt or shaly loam on Brunswick shale. Fractured shale was found several inches below the soil surface in the bottom of the ED02B basin.

The Lansdowne series is a silt loam formed on glacial till, usually in depressional areas. Its high clay content means it can be somewhat poorly drained. ED02A's infiltration rate is only slightly higher than the Lansdowne range. The infiltration rates for the younger sites, PI06 and PI07 are higher than ED02A, but they are still within the same order of magnitude as the maximum reported K_{sat}.

The Parsippany series is a poorly drained member of the Whippany series, consisting of silt loam to clay loam soils formed on glacio-lacustrine deposits. These fine grained soils create slow draining soils as seen in the narrow and low range of the series' K_{sat}. Both of the measurements made at PI05 fall within the reported ranged while two of the PI03 measurements are also close. The third PI03 K_{sat} is five time greater than the other rates for the soil. Macropores created by a medium sized tree growing in the basin close to the sample site could be the source of variation in K_{sat} at PI03. The lack of difference in K_{sat} values between decades may simply reflect the initial conditions of the underlying soils since these soils have low infiltrations rates to begin with, most being poorly to moderately well drained.

There are several confounding effects that may account for the lack of difference in K_{sat} between decades. One potential confounding variable is the land use type and catchment characteristics of each basin (See Table 1). The Nationwide Urban Runoff Program (NURP) (U.S. EPA 1983) compared stormwater pollutant concentrations by land use using data collected from over 80 sites across the country. The study did not find a significant difference between the median TSS concentrations for four land use types identified in the study (residential, commercial, mixed use, and open space/other). However later studies found that stormwater volume (which can be correlated to the extent of impervious surfaces) and high density development can be predictors of TSS concentration in stormwater (Charbeneau 1998, Carle et al. 2005). These studies focused on a much smaller number of watersheds compared to the NURP study and included a higher degree of detail about the watersheds. Site to site variation in stormwater TSS concentrations is high. NURP (U.S. EPA 1983) studies reported median concentrations ranging from 50 to 300 mg/L, a study of a single watershed reported a similar range of 52 to 283 mg/L (Stanley 1996), while a review of stormwater quality studies found concentrations could range from 4 to 1,223 mg/L (Makepeace 1995). Assuming a higher influent total suspended solid concentration (TSS) would increase the amount of clogging in a basin, it is feasible that a younger basin with a greater TSS load could develop a lower infiltration rate more quickly and become comparable to that of an older basin.

There are several factors that go into the design of dry detention basins that influence their ability to remove TSS from stormwater. TSS removal is closely linked to the basin detention time (or drawdown time); Papa and Adams (1995) suggest 22 hours is an optimal detention time to maximize settling in the system while Whipple and Randall (1983) reported a drawdown time of 18 hours could produce 60% TSS removal. After 24 hours, increasing the detention time only marginally improves removal (Papa and Adams 1995). When water ponds in the basin, turbulence in the system can reduce removal rates (Stanley 1996). Since the majority of sediment and other pollutants are washed into a basin during the beginning of a storm (the first flush), basins need to be designed to detain smaller volume storms to facilitate TSS removal (Shammaa et al. 2002). An outlet with multiple orifices accomplishes this purpose by using a small diameter orifice (usually 2.5 to 4 inches) at the base of the outlet for water quality treatment and a larger orifice or weir higher up to manage larger storm events (Kropp 1982). The length to width ratio of the basin as well as its ponding depth also influence TSS removal; longer basins with shallower ponding depths are both effective for increasing sedimentation (Shammaa et al. 2002).

The basins used in this study do vary in their designs (Table 4) which was to be expected since performance standards have changed over the past three decades necessitating modifications in basin design. PI05 and PI06 have more advantageous designs for sedimentation while ED10 has the least. The different sedimentation rates produced by design variations may contribute to differences in clogging and infiltration rates.

Table 4: Basin outlet sizes and length to width ratios

Site	Lower Orifice Diameter (in.)	Middle Orifice Diameter or Dimensions (in.)	Upper Orifice Dimensions (in.)	Length to Width Ratio
ED09	14	-	22 x 42	4:1
ED10	16	-	-	1:2
ED02A	4	14	43 x 41	4:1
ED02B	4	16	43 x 39	1:1
NO01	24	-	-	6:1
NE01				1:1
PI03	14	-	-	3:1
PI05	3	12.5 x 27.5	64 x 54	4:1
PI06	3	9.5 x 30	51 x 51	4:1
PI07	3	24 x 27	42 x 42	2:1

Table 5: Hypothetical sedimentation rates and depths assuming 60% TSS retention.

Catchment : Basin Ratio	**20:1**		**40:1**	
Influent TSS Concentration	50 mg/L	300 mg/L	50 mg/L	300 mg/L
Depth (in.) 10 yrs	0.12 in.	0.75 in.	0.25 in.	1.49 in.
Depth (in.) 30 yrs	0.37 in.	2.24 in.	0.75 in.	4.48 in.

Given their lower anticipated TSS removal rates (60% at best, compared to 100% removal for infiltration basins), it is possible that clogging is less of a problem in detention basins. Table 5 show the potential depths of sediment deposition in a detention basin after 30 years of use along with the numeric assumption used to make the calculations. The influent TSS concentration are the low and high end of the range for residential land use reported in the NURP (U.S. EPA 1983). The calculations also assume that only 60% of the influent mass of TSS remains in the basin. In this system, a high influent TSS concentration and high catchment to basin ratio create the worst case scenario where 4.5 inches of sediment builds up in the basin over the course of thirty years. Depending on the depth of the basin, in this case the new sediment layer could represent 5% to 12.5% of a basin's depth (for 7 and 3 feet of storage, respectively).

The calculations in Table 5 represent estimates of the maximum sedimentation rates for a detention basin. They suggest that the basins used in the study which probably have removal rates less than 60% are probably not going to experience significant clogging caused by sediment deposition. If clogging is not a problem, then there would be little change in the K_{sat} of the basin soils from decade to decade.

Biological activity in the soil may play a role in counteracting the effects of sediment deposition on clogging. The burrowing of invertebrates such as tubicifid worms and the growth and decay of plant roots can create macropores in a soil that would otherwise have a low infiltration rate (Nogaro et al. 2006, Dexter 1991, Lee and Foster 1991, Millward et al. 2011). Plant roots, fungal hyphae, and microbes create and stabilize soil aggregates which can also enhance a soil's infiltration rate (Dexter 1991, Cogger 2005). It is feasible that biological activity may maintain the hydraulic conductivity of a detention basin's soil over time despite the continued addition of sediment. This could explain the lack of change in K_{sat} from decade to decade.

While trading space for time is an economical and more expedient method for comparing the effects of time on the infiltration rate of detention basin soils, numerous confounding factors make it difficult to draw conclusions. There may be too many variables, including influent TSS concentrations and TSS removal rates, that cannot be controlled for and make it unreasonable to compare one site to another. Tracking infiltration rates at individual sites over time or repeating measurements at sites used in previous studies would give a more accurate picture of the evolution of infiltration rates in detention basin soil over time.

CONCLUSIONS

In the ten detention basins used in this study, age did not have an effect on the K_s of the basins' soils. The basins' underlying soils, catchment characteristics, and basin design may all be confounding factors influencing the change in K_s over time at each site. Given the moderate sediment removal rates of detention basins (in comparison to an infiltration basin), it is also possible that clogging caused by sedimentation may not be a significant problem in detention basins. Further study on older basins in well drained soils as well as follow up on previous infiltration study systems is warranted.

Chapter 3 - Testing the performance of 10 to 30 year old stormwater detention basins against New Jersey’s 1983 and 2004 regulatory standards

INTRODUCTION

The construction of buildings, roads, and other hard surfaces alters the hydrology of a landscape in profound and lasting ways. Stormwater management systems such as detention basins are a method of buffering the negative impacts of a developed landscape on the downstream watershed (NRC 2008). Detention basins primarily provide two services to mitigate the negative hydrologic impacts of development: they reduce the rate at which the water leaves a site (referred to as peak flow) and they detain water long enough to allow some suspended sediment and related pollutants to settle in the bottom of the basin. In some situations it is also possible for a basin to recharge groundwater (Livingston et al. 1997). For the purposes of this study, a detention basin’s performance is based on how well it can reduce peak flow, remove total suspended solids, and recharge groundwater.

Since treating peak flow and detaining stormwater are important environmental services, it is reasonable to expect that as long as a hardscape exists, it should have a companion stormwater management system to continue providing environmental protection services. However, not much is known about the service life of stormwater detention basins, that is, when a basin will no longer provide its intended services. A review of guidance documents about stormwater detention basins suggests these systems may have a service life that ranges from 15 to 50 years (See Table 1). Interestingly, in a set of Planning Board minutes, an applicant states that a detention basin could be expected to last for 100 years, though no reference for that age (or any of the others) was provided (Springfield Township 2010). Knowing the service life of infrastructure facilitates is necessary for planning for its replacement to prevent an interruption or loss of service (Lemer 1996).

Table 1: Estimates of detention basin service life from guidance documents.

Service Life or Lifespan	Source
25+ years	City of Roseville 2011
15 years	Qin 2013
50 years	Schueler et al. 1992
20 to 50 years	Miami University 2011
100 years	Springfield Township Planning Commission 2010
20 to 50 years	City of Colorado Spring 2008
30 years	City of Boulder 2002
25 to 50 years	USEPA 2012c

A detention basin can reach the end of its service life when a physical or structural failure occurs. The clogging of piping by debris or collapse, lack of routine maintenance, a loss of volume through sedimentation or slope failure, and the catastrophic failure of an earthen embankment can all prevent a basin from providing its intended services (Livingston et al. 1997). Out of 116 dry detention basins studied in Maryland, 63 were determined to no longer function as designed and 20 had signs of structural failure (Lindsey et al. 1992a). Changes in the structural conditions of detention over time and its influence on service life is the subject of Chapter 4.

Another aspect of service life is the concept of obsolescence – when infrastructure reaches a condition where it no longer provides satisfactory service. Causes of infrastructure obsolescence include regulatory changes, when the performance target changes, and technological change (Lemer 1996). As detailed in Chapter 1, the regulations for stormwater management in the United States have evolved over time in response to new goals for improving water quality. New technologies and practices have also become more popular because of their ability to mimic the natural hydrologic cycle. A detention basin built to meet a particular set of peak flow reduction goals may not be able to fulfill newer water quality goals because of the nature of its design (Kropp 1982). While these basins may continue to function, a new regulatory environment may have rendered them obsolete.

To size, configure, and locate detention basins and other stormwater facilities, engineers and planners rely on design storms to calculate input parameters such as time of concentration, time to peak, and runoff volume. Design storms represent typical rainfall depths and distribution patterns for a given region and are defined based on their return period or frequency of occurrence (Bell 1969). Infrequent events, such as 10 or 100 year storms, that produce large rainfall depths are typically used to size a detention basin for peak flow reduction (Ormsbee 1987). The typical result is a basin built to handle large volumes of water with one main outlet and an emergency spillway for overflow. Figure 1 shows the outlet of a detention basin built for peak flow reduction.

Figure 1: Culvert outlet at ED10.

The majority of a catchment's pollutant load is entrained and transported during the early stages of a storm; Griffin (1980) found that 70% of the total pollutant load will be present in the first 30% of a watershed' runoff volume. This phenomenon is often described as the first flush. In order for a detention basin to improve water quality, it must be designed to detain the first flush volume; however this volume is much smaller than the volumes generated by design storms for peak flow control (Kropp 1982, Griffin 1980). Detention basins primarily improve water quality through removing sediment (often measured and reported as total suspended solids – TSS) which can also contain other pollutants such as phosphorus and metals (Livingston 1997). Designing detention basins with smaller orifices and larger surfaces area improves sedimentation by increasing detention time and decreasing water depth (Curtis and McCuen 1977). However smaller orifices cause too much water back up during larger storms. Multi-stage or dual purpose outlets solve this problem by placing a small orifice at the lowest elevation in the basin to handle smaller storms that produce the higher pollutant loads and then placing a larger orifice or two at higher elevations to drain the basin during larger storms (Kropp 1982). Figure 2 shows a dual purpose outlet.

Figure 2: Box outlet with multiple orifices in basin ED02B.

Retrofitting is one way to address the water quality deficiencies in detention basins originally designed to only treat peak flow while avoiding the construction of a completely new system (NRC 2008). Retrofitting techniques include the replacement of the outlet structure with a multi-orifice riser or a floating riser which drains surface water where the TSS concentration is lower (Guo et al. 2000). Middleton and Barrett (2008) installed an outlet with an automated valve and controller which could provide batch treatment to enhance water quality by prolonging detention time. Modifying the outlet to create a smaller permanent pool in the bottom of the basin to enhance pollutant removal is another retrofit option (Guo 2009). While retrofitting is a viable method for improving the performance of detention basins, a regulatory mandate is needed. Otherwise, property owners have little incentive to install retrofits. Consequently, many detention basins remain in operation despite being obsolete in a regulatory and technological context.

The State of New Jersey updated its 1983 stormwater management rules in 2004 (N.J.A.C. 7:8), by requiring higher reductions for peak flow and TSS removal along with adding a requirement for groundwater recharge. These changes create a condition of regulatory obsolescence for many detention basins in the State. Additionally, no information is readily available on whether or not detention basins built in accordance with the previous rule set from 1983 continue to meet their original standards. To better understand the anticipated service life of detention basins and the current performance of pre-2004 systems in the context of regulatory obsolescence, the goals of this project are to answer the following questions:

- After 10 to 30 years of service, how well do detention basins fulfill the regulatory requirements they were designed to meet?
- How close do older detention basins come to fulfilling new regulatory requirements promulgated after they were built?

METHODS

Performance Targets

For peak flow reduction, New Jersey's 1983 Stormwater Management Rules (1983 Rules) state that a site's post-development peak flow must be less than the peak flow for the pre-development site as calculated for 2, 10 and 100-year design storms. The 2004 Rules required that post-development peak flow must be 50, 75, and 80% of the pre-development peak flow generated by the 2, 10 and 100-year design storms, respectively.

The 1983 Rules for water quality allowed designs to be based on a 1-year design storm or on a 1.25 in. 2-hour storm. A detention basin had to be able to evacuate 90% of the runoff from either of the two storms in "approximately 18 hours" in a residential development or in 36 hours for all other situations. The 2004 Rules require that a site's stormwater system retain 80% of total suspended solids generated at a site. N.J.A.C. 7:8-5.5(b) provides a list of TSS removal efficiencies for different types of structural best management practices; the rules assume a detention basin with a 24-hour detention time removes 60% of TSS. Structural best management practices can be used in series to meet this requirement; two detention basins in series would provide an 84% TSS removal rate. The rules define a system's detention time as the amount of time required to evacuate 90% of the runoff from the 1.25 in. 2-hour storm.

There were no requirements for groundwater recharge in the 1983 Rules. The 2004 Rules provide two options for meeting the recharge requirements. The first option demonstrates that a post-development site will maintain 100% of the average annual recharge of the site before it had been developed. The New Jersey Department of Environmental Protection (NJDEP) provides a spreadsheet based tool for designing an infiltration system to meet this requirement, however it cannot be applied to detention basins (Blick et al. 2004). The second option demonstrates a site will be able to infiltrate the difference between the pre-construction and post-construction runoff volumes from a 2-year storm. The second option was analyzed for this study.

The ability of a site (for peak flow and recharge) and a basin (for water quality) to meet the required target was reported as a yes/no answer and also as a percent of service provided. Percent of service provided was calculated with the following general equation:

$$1 + \frac{(Target - Post\ Dev.\ Model)}{Target} = \%\ Service\ Provided \qquad (1)$$

A result greater than 100% indicates that the post-development result exceeds the target, while a result less than 100% indicates that a system does not meet the target requirement.

Table 2 shows the rainfall depth for the design storms used in the analysis. Note that two depths are provided for each storm since the National Oceanic and Atmospheric Administration updated its precipitation frequency atlases in 2004 based on longer data sets and newer interpolation models (Bonnin et al. 2006). Performance for the 1983 rules was tested using the "old" depths since that data was available when the basins were designed. The "new" storms were used to test performance against the 2004 rules. All the storms follow a Type III distribution pattern in accordance with the Natural Resource Conservation Service's TR-55 runoff calculation guidelines. (NRCS 1986). The 1.25 in. 2-hour storm for water quality design follows a distribution defined by NJDEP in accordance with the 2004 rules (Blick et al. 2004).

Table 2: Design Storm Rainfall Depths for Middlesex County, New Jersey.

Note: The Natural Resources Conservation Service (NRCS) replaced the "Old" storms with the "New" storms in 2004 (NRCS 2005).

	"Old" Depth (in.)	"New" Depth (in.)
1-year	2.7	2.8
2-year	3.3	3.3
10-year	5.2	5.1
100-year	7.5	8.6

Site Description

To test the hypothesis about design, the study created stormwater models of five properties in Middlesex County, New Jersey, listed in Table 3. The sites range in age from 8 to 30 years old. ED02, PI0567 and NO01 are high density residential developments while ED09 is a college campus and ED10 is a commercial site. ED02 and PI0567 both contain multiple detention basins but only one hydrograph can be used to demonstrate compliance with the peak flow requirement. Consequently, each basin was modeled separately to produce a unique hydrograph, which was then added to the other basin's hydrograph to produce a single hydrograph for the property based on the following formula:

$$Q_{A1} + Q_{B1} = Q_1 \qquad (2)$$

Where Q_{A1} and Q_{B1} are discharge (cfs) from basins A and B at timestep 1 and Q_1 is the total site discharge at timestep 1.

Table 3: Characteristics of design study detention basins.

Site	Basin	Installation Year	Basin Area (acres)	Catchment Area (acres)	Percent Impervious Area	Land Use
ED02	ED02A	1993	0.565	7.189	72%	High Density Residential
ED02	ED02B	1993	0.416	7.292	79%	High Density Residential
ED09	ED09	1982	1.768	28.217	26%	College Campus
ED10	ED10	1984	0.095	6.49	88%	Commercial
NO01	NO01	1993	1.356	30.795	72%	High Density Residential
PI0567	PI05	2004	0.497	8.459	58%	High Density Residential
PI0567	PI06	2004	0.755	5.914	61%	High Density Residential
PI0567	PI07	2004	0.513	10.246	60%	High Density Residential

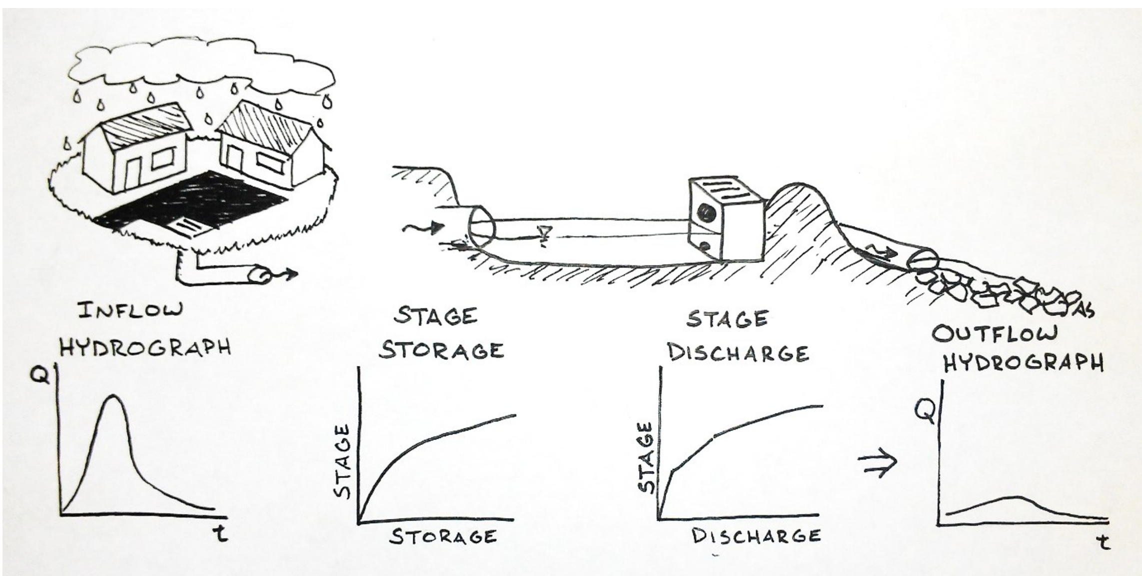
Conceptual Model

The study's stormwater model has three components: an inflow hydrograph, a basin stage-storage relationship, and a stage-discharge relationship. The model tracks the movement of water through the subject property (the basin's catchment area) then into and out of the detention basin as shown in Figure 3. It is based on the continuity equation which states that the mass of water entering the system (I) is equal to the mass of water leaving it (O) plus or minus a change in storage (dS/dt).

$$I - O = dS/dt \tag{3}$$

By assuming the density of water is constant and specifying a length of time, I and O become discharge (volume per time) in and out of the system (Haestad and Durrans 2003).

Figure 3: Stormwater and Detention Basin Conceptual Model.



The three relationships are combined together using the storage-indication method to analytically solve the continuity equation and create outflow hydrographs for each site. The inflow hydrograph describes the rate at which water enters the basin. The stage-storage relationship is based on the topography of the basin and describes the height of water in the basin for a given volume of water. The height of water is needed to determine the stage-discharge relationship which produces the outflow hydrograph. The model components are described in greater detail below.

The models were built and run in the software program HydroCAD 10. The discharge, volume, and storage data collected from each model run were used to test the performance of each basin and site against the New Jersey 1983 and 2004 Rules.

Inflow Hydrograph

The inflow hydrograph represents the stormwater generated by the basin's catchment area for a particular design storm. The boundary of the catchment is defined by the extent of the developed area of the subject property (containing buildings, pavement, or lawn). In order to develop a more accurate site model the property was divided into subcatchments based on the pattern of storm sewer piping and land use at the site (Blick et al. 2004). As an example, Figure 4 shows the arrangement of subcatchments which feed into basin PI07. Each building is a subcatchment connected to the system via drain pipes. The road subcatchments were based on the location of storm drain inlets which the lawn area also drain into. HydroCAD combined the runoff generated by each subcatchment into a single hydrograph that become the inflow into the basin.

HydroCAD calculated runoff from each subcatchment using the SCS TR-20 Unit Hydrograph Method (TR-20). TR-20 uses a specified rainfall depth and pattern along with a catchment's curve number and time of concentration to calculate runoff rates during and after a storm. The method can also calculate the total volume of runoff generated by the storm. A curve number is an empirical parameter which predicts the amount of runoff generated by a site (NRCS 1986). It is influenced by the type of soil and the type of land cover (pavement, grass, etc.); a higher curve numbers indicates a higher volume of runoff. Curve numbers for each site were selected based on each site's hydrologic soil group as determined from a review of soil maps (NRCS 2012) and observations of the site. Table 4 lists the CN selected for each site.

Figure 4: PI07 Subcatchment placement on aerial photo and HydroCAD drainage map.

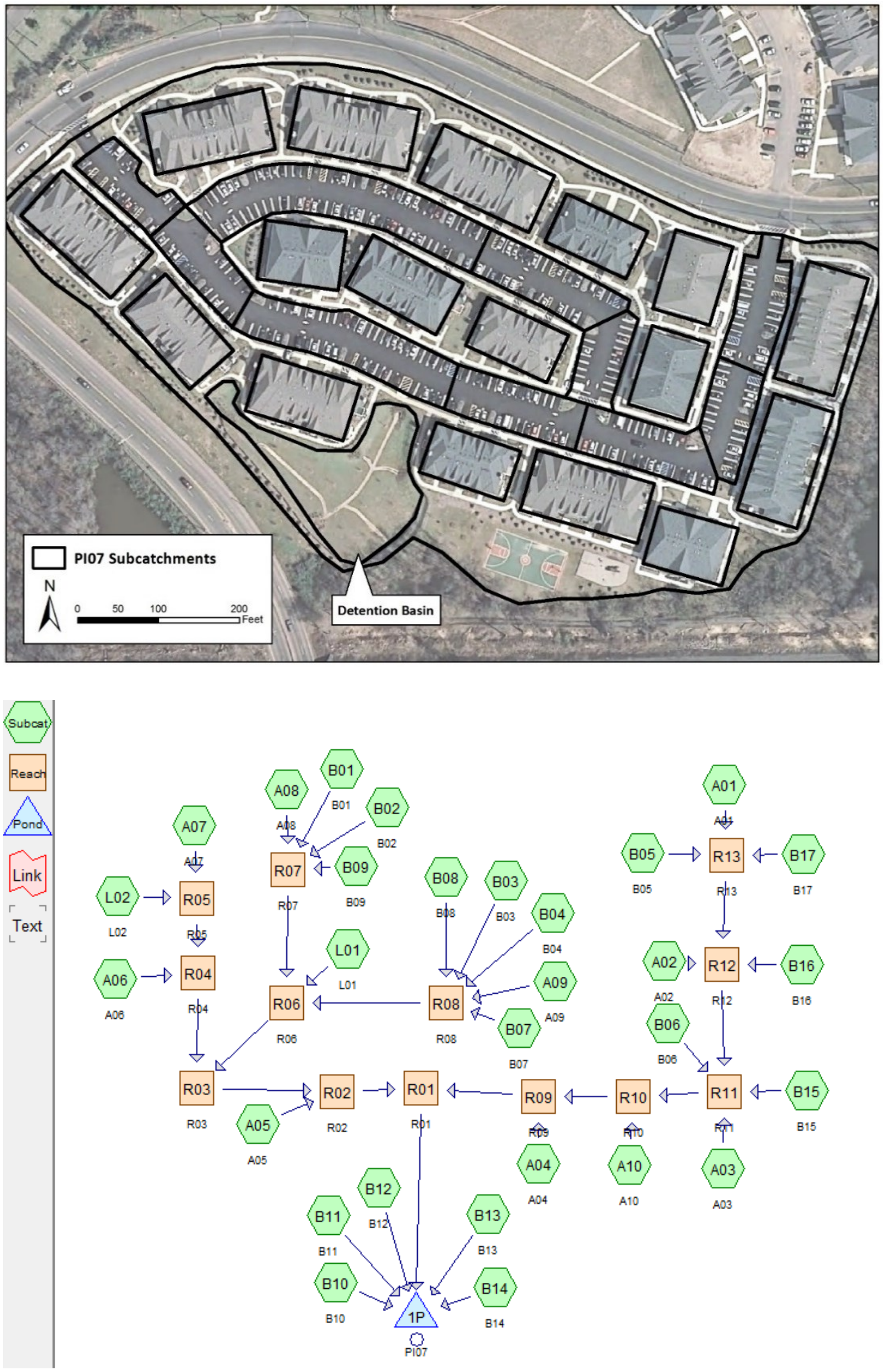
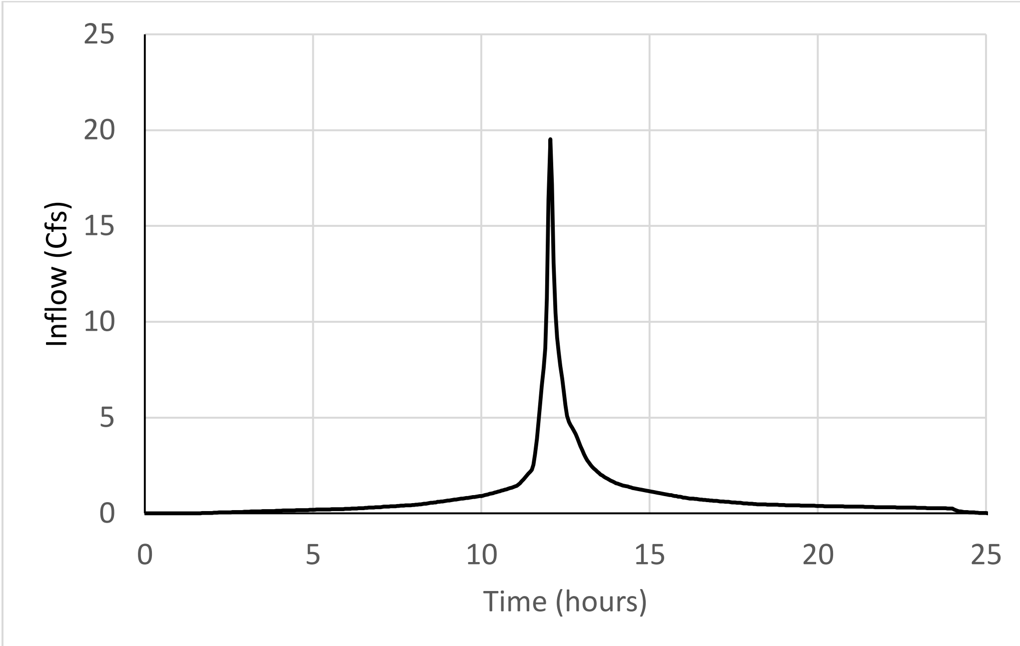


Table 4: Site Curve Number (CN) Selection for Pre and Post Development Scenarios.

Site	Scenario	CN	Description, Condition, Hydrologic Soil Group
ED02	Pre	70	Woods, Good, HSG C
ED02	Post	80	> 75% grass cover, Good, HSG D
ED09	Pre	55	Woods, Good, HSG B
ED09	Post	61	> 75% grass cover, Good, HSG B
ED10	Pre	55	Woods, Good, HSG B
ED10	Post	73	Woods, Fair, HSG C
NO01	Pre	70	Woods, Good, HSG C
NO01	Post	74	> 75% grass cover, Good, HSG C
PI0567	Pre	70	Woods, Good, HSG C
PI0567	Post	74	> 75% grass cover, Good, HSG C
Impervious Surfaces		98	All buildings and pavement

A catchment's time of concentration (Tc) is the time it takes water to travel from the most hydrologically distant point in a catchment to its outlet (NRCS 1986). In this study, calculations for three types of flow were usually needed to determine Tc for a subcatchment: sheet flow, shallow concentrated flow, and pipe channel flow. All three flow types require slope, surface texture, and flow length as input parameters; channel pipe flow additionally needs pipe diameter as an input. As built utility plans were used to determine Tc input parameters for ED02, ED10, and NO01. Since plans were not available for ED09 or PI0567, Tc inputs were estimated during site visits and by making measurements of aerial photography in ArcMap 10. Figure 5 shows an example inflow hydrograph for the PI07 basin.

Figure 5: PI07 Inflow Hydrograph, 2 year design storm.



Stage-Storage Relationship

The stage-storage relationship describes the height of water in the basin (its stage) as the volume of water in the basin varies. A Topcon GTS-240NW total station (electronic transit) and a Getac/Topcon FC-236 field controller were used to survey each detention basin by collecting a set of location and elevation points that were then used to create a topographic map of the basin (see example in Figure 6). The map was made in ArcMap 10 using a spline method to interpolate elevation data from the survey points. The interpolation data was then converted into elevation contours spaced at 0.5 foot intervals using the Contour Tool. The Calculate Geometry Tool provided the area within each contour interval which represents the surface area of the water at a particular elevation (Figure 7) – this is called a stage-area relationship. The stage-area data for each basin was input into HydroCAD which then converted the data into the stage-storage relationship by the conic approximation method. The conic method calculates the volume between two areas as though the two surfaces were cross sections of a cone (Haestad and Durrans 2003). The cumulative volume at each stage becomes the stage-storage chart (Figure 8).

Figure 6: PI07 Elevation Contour Map with 0.5 foot intervals.

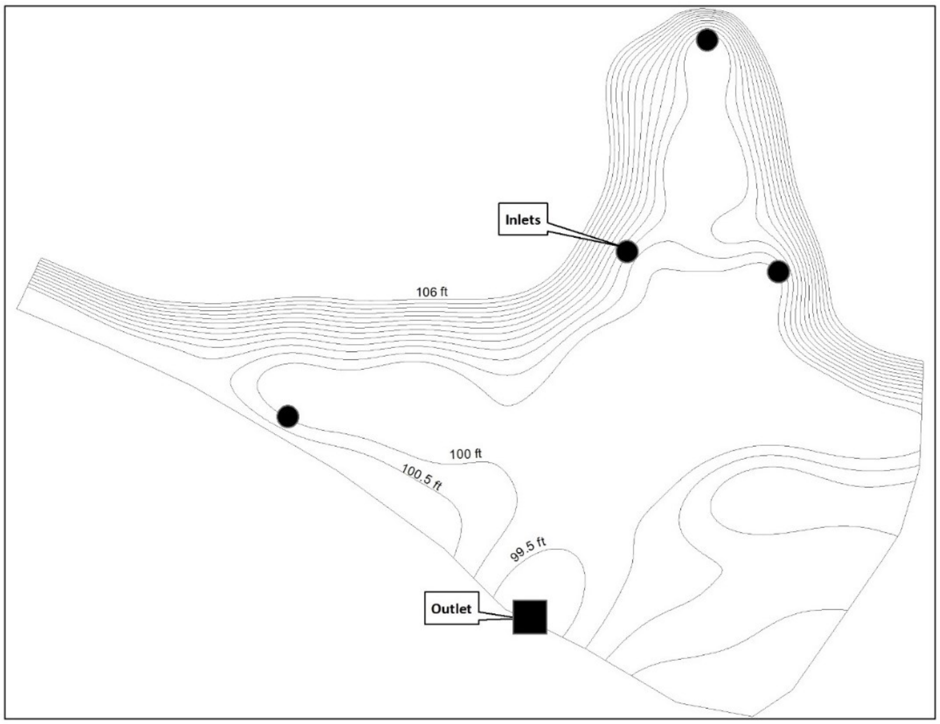


Figure 7: PI07 Elevation Contour Map with 0.5 foot intervals.

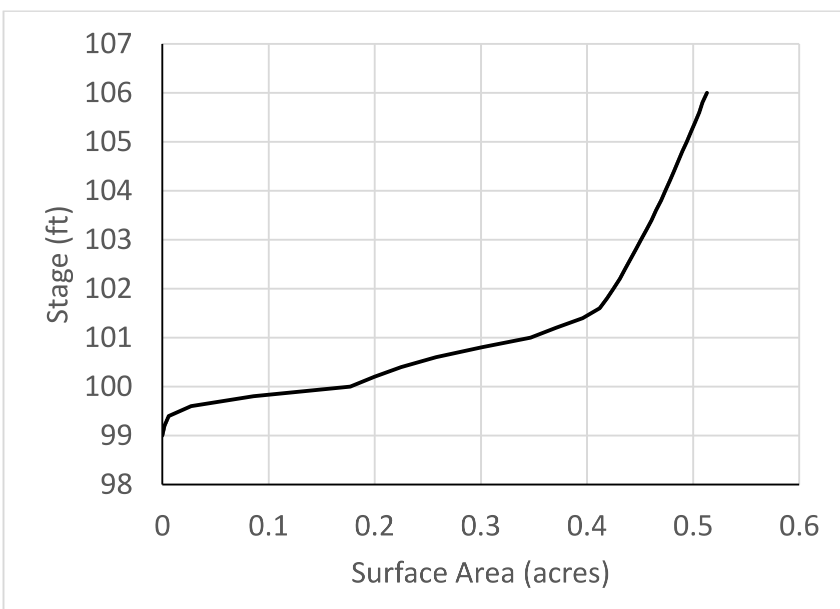
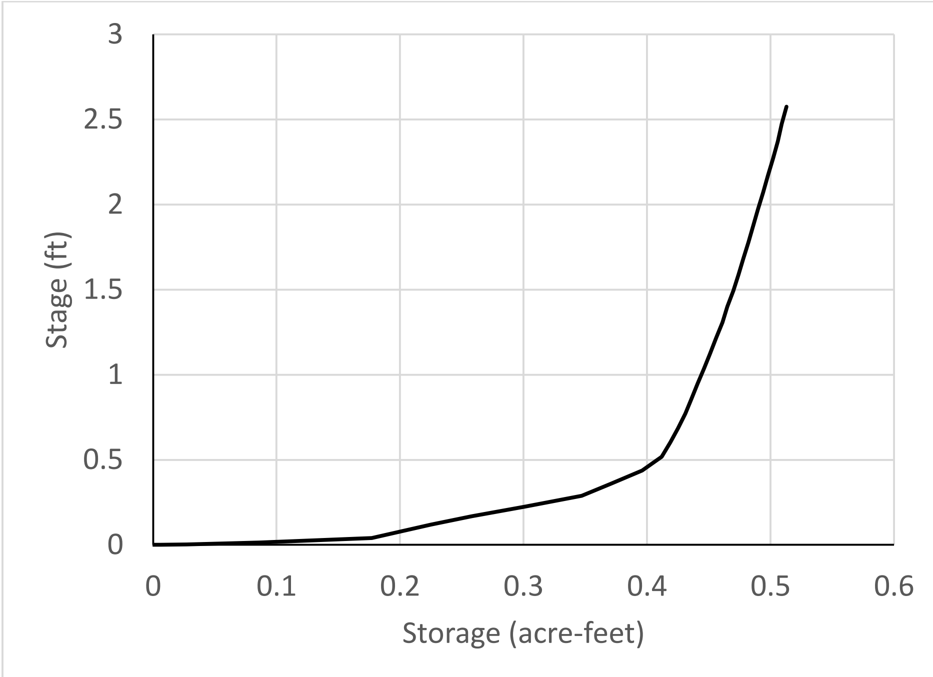


Figure 8: PI07 Stage-Storage Graph.



Stage-Discharge Relationship

The flow of water out of the basin is a function of the water stage at a given time and the configuration of the basin's outlet structure. Two of the study sites had culvert outlets while the other three had box outlets which contained two or three spillways. Flow out of the box openings was governed by equations for weir (rectangular shaped spillway) or orifice (circular shaped spillway) flow. For all of the outlet types, the water stage and dimensions of the openings control the basin's discharge. The slope of the culvert pipe is also needed for outflow calculations. The outlet dimensions and elevations were measured at each site during the survey process. It was assumed that none of the outlets experienced tailwater effects, meaning downstream conditions had no effect on the outlet discharge. The spillway and culvert equations are used to develop the stage-discharge graph (Figure 9).

Water can also leave the basin through exfiltration – soaking into the ground. HydroCAD modeled this process using Darcy's Law, using hydraulic conductivity (K_{sat}) and assuming saturated flow. K_{sat} for each basin was measured with a tension infiltrometer as described in Chapter 2. Table 5 lists the mean K_{sat} values used for each basin. Depth to groundwater (a required input) was assumed to be three feet below the basin's lowest elevation since that is the minimum depth to groundwater allowed for a stormwater infiltration system in the State of New Jersey (Blick et al. 2004). For every design storm, each model was run twice. Once with exfiltration as an additional outlet for water (these models are denoted with an X) and then a second time with no exfiltration.

Figure 9: PI07 Stage-Discharge Graph.

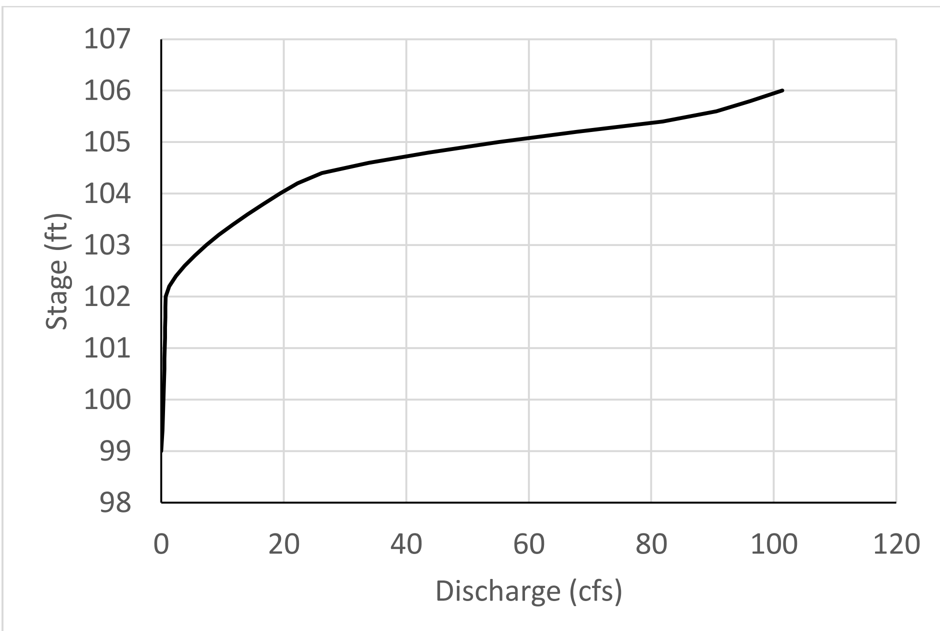


Table 5: Mean Saturated Hydraulic Conductivity (Ksat) of detention basins (based on Chapter 2 infiltration study).

Basin	K_{sat} (in./hr)	Standard Deviation
ED02A	0.29	0.06
ED02B	1.15	0.22
ED09	0.24	0.07
ED10	0.54	0.58
NO01	1.57	1.39
PI05	0.07	0
PI06	0.48	0.56
PI07	0.57	-

Pre-development Hydrographs

The performance standards for peak flow reduction are based on the peak flow generated on the site before it is developed. According to the 1983 Rules, a designer must assume the site is wooded and in good condition when selecting a curve number (CN). The pre-development condition of each site was determine using historic aerial photos available online (Nationwide Environmental Title Research 2009). Land cover of pre-development sites was assumed to be homogenous. The CN chosen for each pre-development site is listed in Table 4. The size of the pre-development catchment was equal to the area of development lot and was calculated using parcel data in ArcGIS 10. USGS Topographic maps were used to determine the pre-development slope of the property. Pre-development ED02 was modeled with three subcatchments based on the original site plans. The hydrographs for each individual subcatchment were added together to produce a single hydrograph which was used to test basin performance. The other pre-development sites were modeled as single catchments.

RESULTS

1983 Rules

Tables 6 and 7 shows the pre-development target peak flows and the corresponding post-development peak flows produced by each site’s stormwater model. These results are based on the “old” NRCS design storm depths. With the exception of ED09, ED10, and NO01 for the 2-year storm, all of the sites produce a post-development peak flow less than the pre-development peak flow for all three storms. Incorporating exfiltration into the models does not change how the sites pass or fail the 1983 peak flow requirement. Exfiltration makes some improvement in the performance of ED02 and PI0567 by increasing the percent service provided for all three storms.

Table 6: 1983 Peak Flow Reduction Results for sites without exfiltration.

Note: Rules require post-development peak flow be less than pre-development peak flow.

Model	Pre-Dev. Peak Flow (cfs)	Post-Dev. Peak Flow (cfs)	Post < Pre?	% service provided
2-year Storm (3.3 in.)				
ED02	14.29	8.14	yes	143%
ED09	1.97	5.87	no	0%
ED10	0.66	3.23	no	0%
NO01	7.12	12.38	no	0%
PI0567	7.1	5.39	yes	124%
10-year Storm (5.2 in.)				
ED02	38.26	25.27	yes	134%
ED09	12.34	11.73	yes	105%
ED10	4.4	3.24	yes	126%
NO01	19.24	15.62	yes	119%
PI0567	19.44	17.72	yes	109%
100-year Storm (7.5 in.)				
ED02	71.7	58.49	yes	118%
ED09	31.93	22.92	yes	128%
ED10	11.39	3.29	yes	171%
NO01	36.34	18.35	yes	150%
PI0567	37.06	36.85	yes	101%

Table 7: 1983 Peak Flow Reduction Results for sites with exfiltration.

Note: Rules require post-development peak flow be less than pre-development peak flow.

Model	Pre Dev Peak Flow (cfs)	Post Dev Peak Flow (cfs)	Post < Pre?	% service provided
2-year Storm (3.3 in.)				
ED02X	14.29	7.45	yes	148%
ED09X	1.97	5.85	no	-97%
ED10X	0.66	3.22	no	-288%
NO01X	7.12	12.1	no	30%
PI0567X	7.1	4.19	yes	141%
10-year Storm (5.2 in.)				
ED02X	38.26	22.85	yes	140%
ED09X	12.34	11.52	yes	107%
ED10X	4.4	3.24	yes	126%
NO01X	19.24	15.22	yes	121%
PI0567X	19.44	15.78	yes	119%
100-year Storm (7.5 in.)				
ED02X	71.7	56.57	yes	121%
ED09X	31.93	22.68	yes	129%
ED10X	11.39	3.28	yes	171%
NO01X	36.34	17.7	yes	151%
PI0567X	37.06	34.22	yes	108%

When using the 1 year design storm, the PI05, PI06, and PI07 basins meet the 1983 water quality requirement to have a detention time of 18 hours as shown in Table 8. ED02A and B have the next longest detention times and may have been considered to meet the requirement given the rule phrasing of a detention time of "approximately 18 hours." Since exfiltration increases the rate at which water leaves the basin, it does not improve detention though it is reasonable to assume soaking water into the soil is still providing some water quality enhancement.

Table 8: 1983 Water Quality Results calculated using the 1-year design storm (2.7 in.)

Note: Basin must have 18 hour detention time to fulfill 1983 Water Quality Requirement. X indicates model includes exfiltration.

Model	Detention Time (hr)	Model	Detention Time (hr)
ED02A	15.15	**ED02AX**	13.9
ED02B	13.25	**ED02BX**	9.5
ED09	4.15	**ED09X**	4.05
ED10	11.8	**ED10X**	11.75
NO01	3.95	**NO01X**	3.35
PI07	20.8	**PI07X**	11.7
PI05	25.9	**PI05X**	24.65
PI06	24	**PI06X**	15.85

2004 Rules

The 2004 Rules set more stringent peak flow reduction targets. A site's post-development peak flow must be 50%, 75%, and 80% of the 2, 10, and 100-year pre-development peak flows. The results of this analysis are shown in Tables 9 and 10. None of the sites meet their 2 year targets, though ED02 and PI0567 come the closest providing 86 and 45% of their expected services. Percent services provided for ED09, ED10 and NO01 are reported as zero to avoid using negative percentages given the large gap between the pre and post-development peak flows. These three sites are all providing peak flow reduction, but it is not nearly adequate to meet the 2-year standard. ED02 is the only site to meet the 10 year target; though ED10's peak flow is within 4% of its 10 year target while NO01 is within 11%. ED02, ED09 and ED10 all meet the 100 year target; including exfiltration allows NO01X to also pass as well.

Table 9: 2004 Peak Flow Reduction Results for sites without exfiltration.

Note: Rules require post-development peak flow be 50, 75, and 80% of the pre-development peak flows for the 2, 10, and 100-year storms, respectively.

Model	Pre-Dev. Peak Flow (cfs)	Target Peak Flow (cfs)	Post-Dev. Peak Flow (cfs)	Post < Target?	% service provided
2-year Storm (3.3 in.), 50% of Pre-Dev					
ED02	14.30	7.15	8.14	no	86%
ED09	1.98	0.99	5.87	no	0%
ED10	0.66	0.33	3.23	no	0%
NO01	7.12	3.56	12.38	no	0%
PI0567	7.10	3.55	5.39	no	48%
10-year Storm (5.1 in.), 75% of Pre-Dev					
ED02	36.91	27.68	23.61	yes	115%
ED09	11.63	8.72	10.98	no	74%
ED10	4.15	3.11	3.23	no	96%
NO01	17.83	13.91	15.48	no	89%
PI0567	18.72	14.04	16.97	no	79%
100-year Storm (8.3 in.), 80% of Pre-Dev					
ED02	88.44	70.75	63.67	yes	110%
ED09	42.70	34.16	25.87	yes	124%
ED10	15.30	12.24	3.37	yes	172%
NO01	44.98	35.98	42.57	no	82%
PI0567	45.98	36.78	50.45	no	63%

Table 10: 2004 Peak Flow Reduction Results for sites with exfiltration.

Note: Rules require post-development peak flow be 50, 75, and 80% of the pre-development peak flows for the 2, 10, and 100-year storms, respectively.

Model	Pre-Dev. Peak Flow (cfs)	Target Peak Flow (cfs)	Post-Dev. Peak Flow (cfs)	Post < Target?	% service provided
2-year Storm (3.3 in.), 50% of Pre-Dev					
ED02X	14.30	7.15	7.45	no	96%
ED09X	1.98	0.99	5.85	no	0%
ED10X	0.66	0.33	3.22	no	0%
NO01X	7.12	3.56	12.1	no	0%
PI0567X	7.10	3.55	4.85	no	63%
10-year Storm (5.1 in.), 75% of Pre-Dev					
ED02X	36.91	27.68	21.88	yes	121%
ED09X	11.63	8.72	10.79	no	76%
ED10X	4.15	3.11	3.23	no	96%
NO01X	17.83	13.91	15.09	no	91%
PI0567X	18.72	14.04	16	no	86%
100-year Storm (8.3 in.), 80% of Pre-Dev					
ED02X	88.44	70.75	62.6	yes	112%
ED09X	42.70	34.16	25.62	yes	125%
ED10X	15.30	12.24	3.37	yes	172%
NO01X	44.98	35.98	18.71	yes	148%
PI0567X	45.98	36.78	48.21	no	69%

Table 11: 2004 Water Quality Results calculated using the 1.25 in. 2-hour design storm.

Note: A site must have 80% TSS removal rate to fulfill 2004 Water Quality Requirement.

Model	Detention Time (hr)	TSS Removal (%)	Model	Detention Time (hr)	TSS Removal (%)
ED02A	6.85	-	**ED02AX**	6.15	-
ED02B	6.65	-	**ED02BX**	4.45	-
ED09	1.35	-	**ED09X**	1.35	-
ED10	1.1	-	**ED10X**	1.1	-
NO01	1.55	-	**NO01X**	1.4	-
PI07	9.9	-	**PI07X**	7.05	-
PI05	13.3	42.2%	**PI05X**	12.55	40.9%
PI06	9.65	-	**PI06X**	7.05	-

Table 11 contains the detention times and TSS removal rates for each basin. TSS removal could only be calculated for PI05 since its detention time was greater than 12 hours, though its 40% TSS removal is not sufficient for the 2004 Rules (80% TSS removal). It is reasonable to assume that given the very short detention times for ED09, ED10, and NO01 that their TSS removal is negligible.

None of the five sites are able to meet the 2004 Rules for groundwater recharge as shown in Table 12. Notably for a 2-year storm, ED02X and PI0567X are able to infiltrate 27 and 33% of their excess runoff volumes, respectively.

Table 12: 2004 Groundwater Recharge results calculated using 2-year storm (3.3 in.).

Note: To meet the requirement, a site must infiltrate the difference between the post-development and pre-development volumes.

Model	Pre Dev - Post Dev Vol (af)	Recharge Vol (af)	Target < Recharge?	% service provided
ED02X	1.804	0.481	no	27%
ED09X	2.412	0.027	no	1%
ED10X	1.223	0.004	no	0%
NO01X	3.867	0.679	no	18%
PI0567	2.534	0.916	no	36%

DISCUSSION

Peak Flow Reduction

The intention of peak flow reduction or attenuation is to reduce the velocity of runoff from developed land which would otherwise damage stream and river channels. This was an early goal of stormwater management and can be thought of as low hanging fruit; treating nonpoint source pollutants in runoff and reducing stormwater volume are more challenging goals (NRC 2008). McCuen (1979), Akan (1994), and Tillinghast et al. (2011), among others, have criticized peak flow reduction because stormwater volume and higher frequency small storms contributes significantly to stream erosion. According to NJDEP, requiring post-development peak flows to be less than the pre-development peak flows should address problems associated with excess stormwater volume (36 N.J.R. 670a).

At the outset of the project, it was assumed that all sites were designed to completely fulfill all of the 1983 Rules. However given the disparity between the pre and post-development flows for ED09, ED10, and NO01 it is possible that at the discretion of the relevant regulating agency, the sites were simply not designed to treat the 2-year storm. ED10 and NO01 have similar outlet structures, a single culvert, but since NO01 has a much larger basin (1.356 acres) and catchment area (30.795 acres) it comes much closer to meeting the 1983 2-year target. ED10's poor performance for the 1983 2-year storm may also be attributed to volume loss in its basin caused by slumping of an adjacent slope. While ED09 has a box style outlet, it cannot meet the 1983 2-year target because the lower orifice is too large (14 inches), especially when compared to the three and four inch orifices in the box outlets of ED02 and PI0567.

Another possible explanation for the discrepancy could be the differences in modeling procedures. Before modeling development was based on separate pervious and impervious subcatchments, it was common practice to model a site with a weighted curve number calculated from the ratio of pervious and impervious surface. The weighted curve number method underestimates runoff which may explain why the basin models made in this study do not comply with the 1983 requirements.

The small orifices at the bases of the ED02 and PI0567 outlets allow them to come closest to producing a peak flow that is half of the pre-development peak flow. In order to prevent clogging, detention basin orifices cannot be smaller than three inches; requirements can be waived if a smaller outlet would be needed to meet them. These two sites have probably maxed out their performance for the 2004 2-year requirement. Retrofitting similar box style outlets onto ED09 and NO01 is probably feasible given the size of the basins. However ED10 is shallower and has less storage available so a smaller orifice might not be feasible.

The larger outlets on ED09, ED10 and NO01 are better at attenuating the 10 and 100-year peak flows. It is worth note that while the sites do not meet the 2004 10-year peak flow reduction, they all come within 26% of the target. While NO01 does not initially meet the 2004 100-year target, it can when exfiltration is incorporated into the model. The large difference between the two models' post-development peak flows can be attributed to the large depth of ponded water in the basin (6.5 feet) which increases the rate of infiltration since the model is based on Darcy's Law.

The three design storms are treated with equal weight under both the 1983 and 2004 Rules but Emerson (2005) points out that the 10 and 100 year storms may represent less than 7% of annual precipitation. While all of the basins are able to treat the larger scale storms, the 2004 2-year design analysis shows they effectively leave the majority of a region's storms untreated throughout the year. These untreated, frequent small events can contribute to stream erosion and instability even when flooding does not occur (Tillinghast et al. 2011).

Another potential driver of obsolescence is climate change. This can be seen in Table 13 which compares the post-development peak flows calculated using the "old" (7.5 in.) and "new" (8.3 in.) 100-year design storms. When tested against the pre-development flows calculated with the "old" storm, NO-01 and PI0567 are no longer in compliance.

Table 13: Comparison of post-development peak flows generated by "old" (7.5 in.) and "new" (8.3 in.) 100-year design storm.

Note: Pre-development Peak flow is based on "old" storm.

Model	Pre Dev Peak Flow (cfs)	"Old" Post Dev Peak Flow (cfs)	"New" Post Dev Peak Flow (cfs)	% Service for "old" storm	% Service for "new" storm
ED02	71.7	58.49	63.67	118%	111%
ED09	31.93	22.92	25.87	128%	119%
ED10	11.39	3.29	3.37	171%	170%
NO01	36.34	18.35	42.57	150%	83%
PI0567	37.06	36.85	50.45	101%	64%

Water Quality Standards

The 2004 Rules implement stricter water quality standards by allowing only the 2-hour design storm to be used and requiring 80% of TSS to be removed by a treatment system. The previous rules allowed designers to choose between the 2-hour or the 1-year design storm and based the performance metric solely on detention time. In 1983, a detention basin with an 18 hour detention time provided sufficient water quality treatment but in the 2004 Rules a basin would need 24 hours of detention and even then multiple basins or alternate facilities would be necessary to meet the 80% removal goal. The 2004 Rules update causes 5 of the basins used in this study to fall out of compliance for improving water quality.

When describing the water quality control and flood control standards, the 1983 Rules assume detention basins are the default stormwater best management practice of choice; alternatives to detention basins are listed in a separate section. The 2004 Rules account for new technologies such as bioretention systems and constructed stormwater wetlands; these systems are assigned higher TSS removal rates (up to 90%) meaning that only one bioretention system would be needed for compliance as compared to two detention basins set in series. Here again is another example of detention basins becoming technologically obsolete.

Retrofitting the basin outlets with smaller orifices is one potential option to increase detention time (Guo et al. 2000) though there is a minimum allowable orifice size (2.5 inches) under New Jersey rules. However even if a 24-hour detention time could be achieved, that basin alone would still not fulfill the 2004 water quality rules.

While detention basins are limited in their ability to remove TSS regardless of their design, implementing non-structural best management practices (also referred to as source controls) at sites with obsolete systems could be a reasonable alternative to replacement or a complement to retrofitting. In a stormwater context, source controls are practices that prevent runoff from entraining pollutants thereby reducing pollutant loading into waterbodies (Haestad and Durrans 2003). Examples of source controls include street sweeping, catch basin or storm drain cleaning, and homeowner education about vehicle cleaning and lawn maintenance (USEPA 2012d). Unfortunately, limited data is available on the pollutant removal performance of nonstructural best management practices (Clary and Leisenring 2012, Taylor and Fletcher 2007). These methods are often difficult to consistently quantify because they are behavior based and can vary with time (Haestad and Durrans 2003). If future research could better quantify the pollutant removal of a practice such as storm drain cleaning, the techniques could be used in conjunction with a detention basin to reduce pollutant loading from a site. This could potentially allow a site to perform equivalently to the 2004 Rules for water quality.

Groundwater Recharge

Maintaining groundwater recharge rates after site development was a completely new addition to the 2004 Rules. The use of stormwater best management practices which promote infiltration (e.g. bioretention basins) have seen expanded usage because of a growing interest in recharging aquifers and maintaining base flow in streams and rivers (Davis 2009). Infiltrating stormwater is also a viable method for reducing the excess volume of runoff generated by impervious surfaces. Increases in stormwater volume from developed watersheds is associated with flooding and stream erosion (McCuen 1979). While volume problems can be addressed through detention basin design, the result is larger basins that require more space than their peak flow reducing counterparts (Akan 1994).

Though none of the sites were designed to recharge groundwater, when accounting for the hydraulic conductivity of each basin's soil two of the sites are able to infiltrate about a third of the excess stormwater volume generated by the 2-year design storm. While this infiltration does not fulfill the regulatory requirement, the systems are nevertheless providing an additional service beyond their original design. Infiltration at the other sites could be enhanced by encouraging the growth of other forbes and woody plants with deeper root systems (Bartens 2008).

CONCLUSION

If the assumption that the 2-year storm requirements were waived for ED09 and ED10, the oldest sites in the study, then the analysis shows that after 30 years these basins are still able to meet their original peak flow reduction standards. However, basin design severely limits the ability of the older basins from meeting the 2004 peak flow requirements. While the basins continue to function as intended after three decades, changing requirements and design methods suggest obsolescence should play a more important role in determining service life.

Chapter 4 – Structural and Maintenance Conditions of 10 to 40 year old Stormwater Detention Basins

INTRODUCTION

Chapter 3 introduced the idea that the service life of detention basins can be influenced both by regulatory and technological obsolescence and by physical conditions. The previous chapter focused on changes in the regulatory landscape of stormwater and the inability of older detention basins to meet new performance standards. This chapter examines the potential for physical deterioration to affect the performance of detention basins.

As Bracmort et al. (2004) point out, “Water quality problems are often considered ‘solved’ when [best management practices] BMPs are implemented. However, the solution or effectiveness of the BMP may only last a short time.” In their study of agricultural best management practices (BMPs), while two-thirds of the original BMPs were in fair condition the remaining one-third were missing. These results imply that the study’s watershed is receiving one-third less of the intended benefits of BMP implementation. It is unreasonable to assume stormwater detention basins and other BMPs will function indefinitely, estimating the service life of these systems is necessary to plan for the replacement of these systems and prevent loss of service.

Other stormwater BMPs have been the subject of research on service life, particularly those that rely on infiltration as their primary treatment mechanism. Using mathematical modeling, Golroo and Tighe (2012) estimate the service life of porous concrete pavement to be about 9 years. Jenkins et al. (2010) found that after nine years a bioretention basin’s infiltration rate had not significantly decreased. While most detention basins are not designed for infiltration, the results of Chapter 2 suggest that detention basins may be able to maintain moderate infiltration rates for over three decades.

The primary concerns for the condition of detention basins are the condition of their physical structures – its inlets, outlet, and low flow channels – and the buildup of material such as trash (Livingston et al. 1997). The fluctuating water levels of detention basins, the potential for high chloride content in stormwater from deicing material, and freeze thaw cycles all threaten the integrity of concrete structures in detention basins (USACE 1995).The reinforced concrete used to make outlet structures and inlets is vulnerable to corrosion if poorly manufactured.

Maintenance practices for detention basins can include lawn mowing, sediment removal from low flow channels, removing litter and plant debris, replanting exposed soil, and clearing blocked orifices (USEPA 2012c). Neglecting maintenance can result in clogging and undesirable ponding, loss of storage volume, and an unsightly facility viewed as a nuisance (Livingston et al. 1997). In a survey of agricultural BMPs, Jackson-Smith et al. (2010) found that 20% of implemented BMPs were no longer used or maintained after at least 10 years. Under New Jersey regulations, maintenance is the responsibility of the property owner. While maintenance is a requirement, at the State level there are no financial resources available for maintenance by property owners. However the rules also lack an inspection or enforcement program. Lack of disincentive and low incentives may result in low maintenance rates in detention basins.

To better understand the potential service life of stormwater detention basins, the goal of this project is to compare the structural and maintenance conditions of older and newer basins. The project specifically tests the null hypothesis that there is no difference in the conditions of basins based on age. The project utilizes a strategy of trading space for time since it is unfeasible for this project to track basin condition for over years, though perhaps such a program should be started. The first dataset used in the project was collected in Middlesex County by the study author using a short, 7 question inspection form developed by the author with a stronger focus on structural condition. The second dataset was collected by staff and students of the Rutgers Cooperative Extension Water Resource group using a more extensive questionnaire which covers maintenance conditions in greater detail.

METHODS

Middlesex County Detention Basin Condition Study

Thirty-two detention basins were identified in Middlesex County, New Jersey for the first conditions assessment study. The basins were located in residential, commercial, and highway areas and ranged in installation year from 1983 to 2011. The surrounding land use, size, planting condition, and age of each site is detailed in Table 1. Site inspections were conducted from June to October 2012.

The inspection form contains seven questions; the questionnaire used for each site is included in Appendix B. Two questions require the inspector to visually estimate the amount of damage to the inlets and the outlet of each site. Damage is ranked on a scale of 1 to 5 to reflect the amount of spalling, or missing concrete. The scoring system works as follows: 1 indicates no damage, 2 is for 1 to 25% damage, 3 is 26-50%, 4 is 51-75%, and 5 is 76-100% damage. Visual estimation was chosen for its ability to provide a rapid assessment though its accuracy can vary from person to person. Including a visual reference in the questionnaire form was intended to help improve accuracy. When a basin had multiple inlets, each inlet was assigned an individual damage score.

The three other questions identify the presence or absence of accumulated sediment, litter, or debris in or around the inlets, low flow channel, and outlet. The questionnaire also asks the inspector to identify if the basin has trash racks and low flow channels. A score of 0 indicates absence while 1 indicates presence of the condition. For the purposes of this study, photos of each site and its conditions were taken for reference purposes.

Table 1: Age, surrounding land use, and vegetation condition of Middlesex County study sites.

Site ID	Installation Year	Land Use*	Vegetation**
ED01	1983	R	T
ED02A	1993	R	T
ED02B	1993	R	T
ED08	1998	R	T
ED10	1984	C	T
ED12	1987	C	T
ED20	1998	R	T
H01	2007	H	N
H02	2009	H	N
H03	2009	H	N
H04A	2004	H	N
H04B	2004	H	N
H08	2009	H	N
H17	2006	H	N
H21	2004	H	N
H22	2011	H	N
NE01	1996	R	N
NO01	1993	R	T
NO02	1991	R	N
NO03	1995	R	T
NO04	1995	R	T
NO05	1995	R	T
NO06	1995	R	T
NO08	1998	R	T
NO10	1983	R	T
NO11	2009	R	T
NO12	1998	R	T
PI01	1998	R	T
PI03	2004	R	T
PI05	2004	R	T
PI06	2004	R	T
PI07	2004	R	T

* R = residential, H = highway, C = commercial.

** A “turf” (T) site is predominantly covered with grass that is mowed regularly while a “naturalized” (N) site contains nonturf, often wetland vegetation that is not regularly mowed.

Adding the scores from the five questions together creates an overall composite conditions score for each basin:

$$Composite\ Score = Outlet\ Score + \frac{\sum Inlet\ Scores}{Number\ Inlets} + \sum Accumulation\ Scores \quad (1)$$

The highest, and worst, possible score is 8 while the lowest (best) is 1. The inlet and outlet damage scores were given more weight than the accumulation scores since sedimentation and debris can be removed from the basin, while concrete damage is more permanent. For the purposes of analysis, a composite damage score and accumulation score were also calculated:

$$Composite\ Damage\ Score = Outlet\ Score + \frac{\sum Inlet\ Scores}{Number\ Inlets} \quad (2)$$

$$Composite\ Accumulation\ Score = \sum Accumulation\ Scores \quad (3)$$

Hamilton Township Study

The Rutgers Cooperative Extension (RCE) Water Resource Program developed an assessment protocol for inspecting detention basins in Hamilton Township, Mercer County, New Jersey in order to identify failing stormwater systems and identify opportunities for retrofits (Bergstrom 2012). They produced a 23 question inspection form about a site's basin, inlets, outlet, emergency spillway, and outfall area (provided in Appendix C).

In the summer of 2012, Water Resource Program students and staff completed assessments of 100 detention basins in the northern section of the township. The program shared the raw data collected during the inspections for analysis in this study because of the larger sample size and the spread of basin installation years, ranging from 1960 to 2002. Out of the 100 original sites, 33 sites were removed if their age could not be determined, were wet ponds (permanent pools of water), could not be accessed, or had no outlet structure. Basin age was determined based on year built data available in tax assessment records or through historic aerial photography available online (Nationwide Environmental Title Research 2009). Based on the availability historic photography, sites without age related tax data were assigned into one of four age groups shown in Table 2. Since the aerial photo age groups were unevenly distributed, they were reassigned to a decade also shown in Table 2.

Table 2: Range of available historic aerial photography used to estimate installation year of detention basins in Hamilton Township and corresponding decade assignments.

Aerial Photo Year Range	Assigned Decade Group
1970-1979	1970s
1979-1995	1980s
1995-2002	1990s
2002-2006	2000s

Statistical Analysis

Since the majority of the data collected in both studies was frequency data, a chi-square test of association was used to test the null hypothesis that no association occurs between two particular conditions. An example test is the comparison the frequency of occurrence of outlet sedimentation and standing water in Hamilton Township basins. Chi-square tests were calculated in Excel using a built-in statistical function.

RESULTS

Middlesex County Basins

Table 3 summarizes the results of the condition assessment of 32 detention basins in Middlesex County by providing the mean scores of inlet and outlet conditions and the frequency of occurrence of sedimentation or debris in the inlets, channel, and outlets. Out of the basins which have channels, channel sedimentation is the most frequently occurring condition, follow by inlet sedimentation. Basin ED10 (built in 1984) had the worst outlet condition score of 4 while PI03 (2004), NO01 (1993), and ED 20 (1998) all contained inlets with a score of 3.

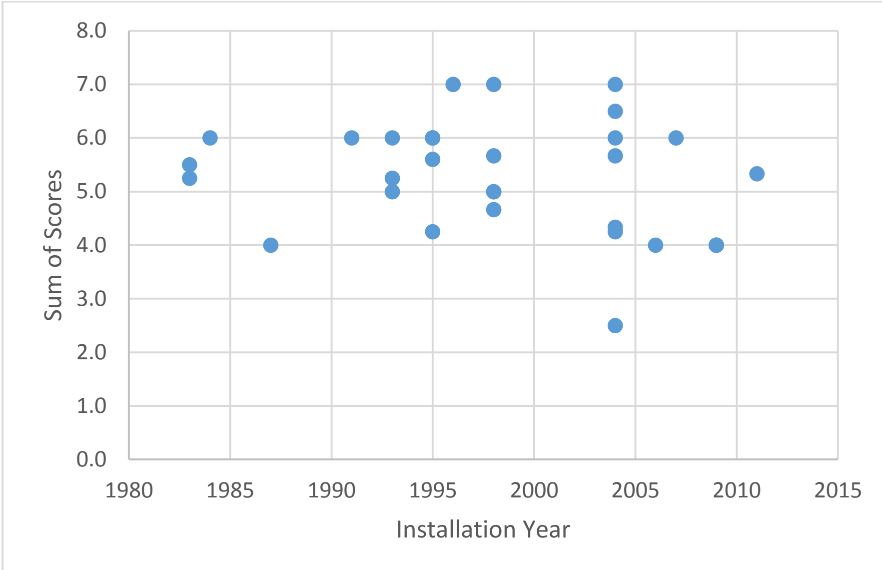
Table 3: Summary results of Middlesex County Conditions Survey (n = 32).

Note: percent of channel sedimentation is calculated based on number of basins with channels, not total number of basins.

Condition	Mean Score	Frequency	Percent of Total
Inlet Structure (Scale: 1 to 5)	1.7		
Outlet Structure (Scale: 1 to 5)	2		
Inlet Sedimentation (presence/absence)		22	69%
Channel Sedimentation (presence/absence)		15	88%
Outlet Debris (presence/absence)		18	56%

Figure 1 shows the composite condition scores for the 32 Middlesex County basins arranged as a function of the basin installation year. There is effectively no relationship between composite score and basin age ($r^2 = 0.0789$). The lower number of study sites built in the 1980s and the wide spread in scores for the 2004 cohort contribute to the extremely low r^2 value. For the dataset, the composite condition score does not disprove the null hypothesis that basin condition does not change over time. The concrete composite score and the debris composite score also lack correlation with basin installation year (Figures 2 and 3, respectively).

Figure 1: Composite conditions scores for Middlesex County detention basins by installation year



Figures 4 and 5 group the sites by decade to compare the frequency of occurrence of inlet sedimentation, outlet debris, trash racks, and channel sedimentation. Again, there appears to be no relationship between age and condition. Inlet sedimentation occurs slightly more frequently than outlet debris. A chi-square test of association rejects the null hypothesis that there is not association between outlet debris and trash racks ($p = 0.015$), which suggests that trash racks are performing their intended purpose.

Figure 2: Concrete composite scores for Middlesex County detention basins as a function of installation year.

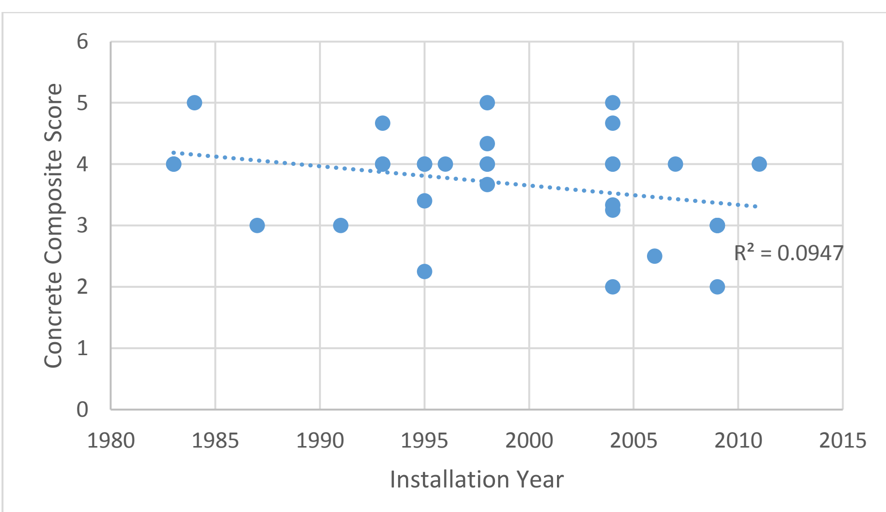


Figure 3: Debris composite scores for Middlesex County detention basins as a function of installation year.

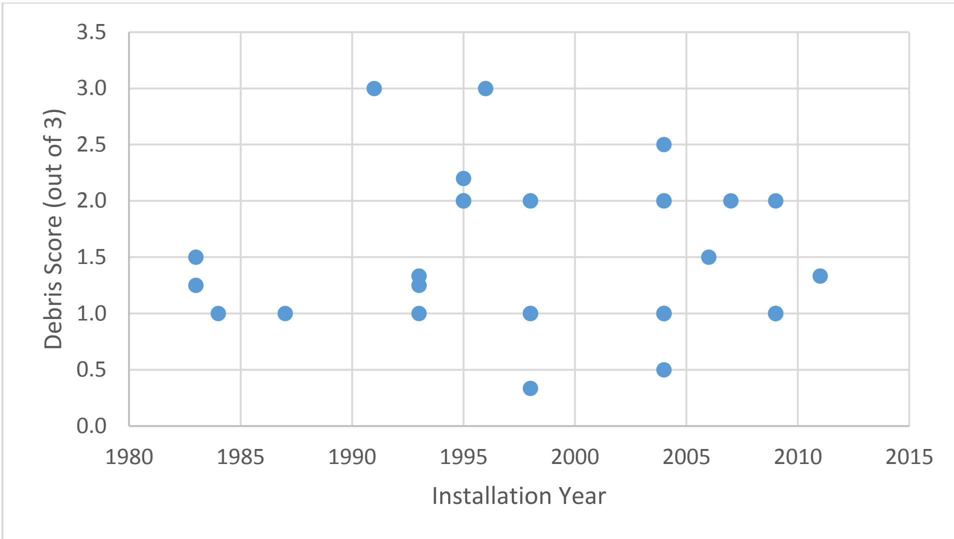


Figure 4: Occurrence of inlet sedimentation, trash racks, and outlet debris by decade in Middlesex County study.

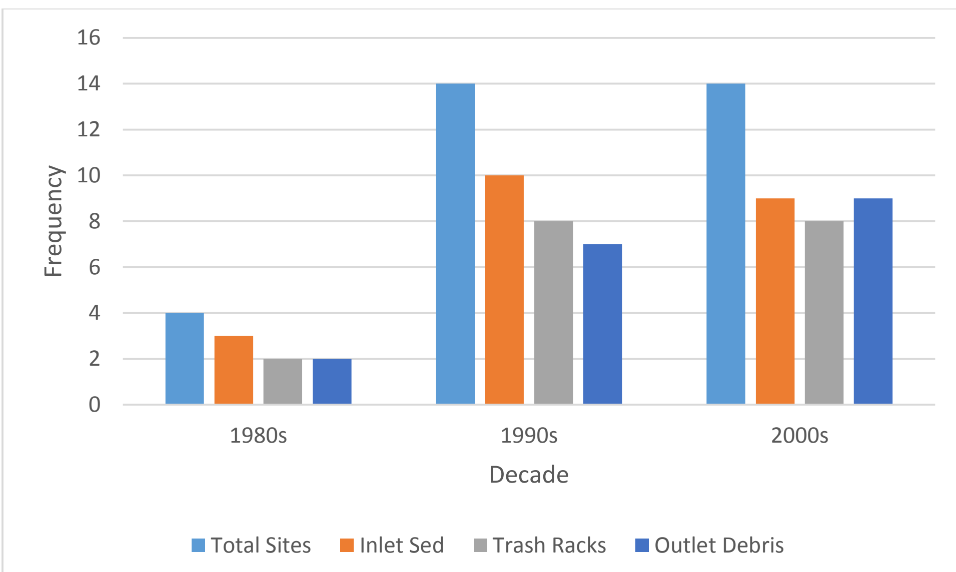
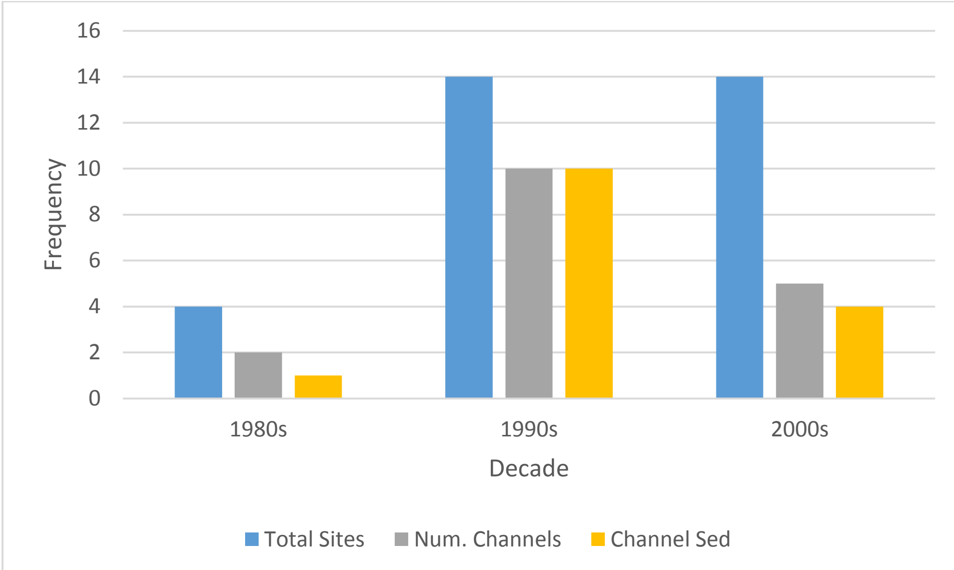


Figure 5: Occurrence of channel sedimentation by decade in Middlesex County study.



Hamilton Township Basins

Table 4 presents the results of the conditions assessment of detention basins in Hamilton Township. Debris or sediment accumulation in or around the outlet was the most frequent condition found at 60% of the 67 basins. The other most prevalent conditions include the presence of a low flow channel (55% of all sites), sediment accumulation in the basin (42%), debris or sediment accumulation in or around the inlet (40%), and the accumulation of debris or litter in or around the outlet (36%). These conditions are present in all age groups. Reports of the basin not functioning, basin wall erosion, and tree growth close to pipes were the only conditions that appear in a single decade. Both basin wall erosion and tree growth occur in the 1970 group while reports of the basin not functioning occurred for two 1990s basins.

Damage to the inlets and outlets was reported for 13% and 22% of the basins, respectively. Figure 6 shows the distribution of inlet and outlet damage by age group; the histogram does not suggest a strong pattern between time and frequency of damage. The analysis of the effects of time on condition is hindered by the uneven distribution of sites in the study's age groups. Problems with erosion occur more frequently around the inlets (16%) and the outlets (16%), compared to the basin walls (3%) and outfall (3%).

Chi-square tests of association rejected the null hypotheses that there was no association between inlet sedimentation and basin sedimentation ($p = 0.00003$), inlet sedimentation and outlet sedimentation ($p = 0.01$), outlet sedimentation and basin sedimentation ($p = 0.0001$). The test also rejected the null hypothesis of no association for the presence of outlet sediment and standing water ($p = 0.02$) and outlet debris and standing water ($p = 0.05$). The test failed to reject the null when comparing the presence of low flow channels and sedimentation in the various basin components, as well as the presence of standing water and sedimentation.

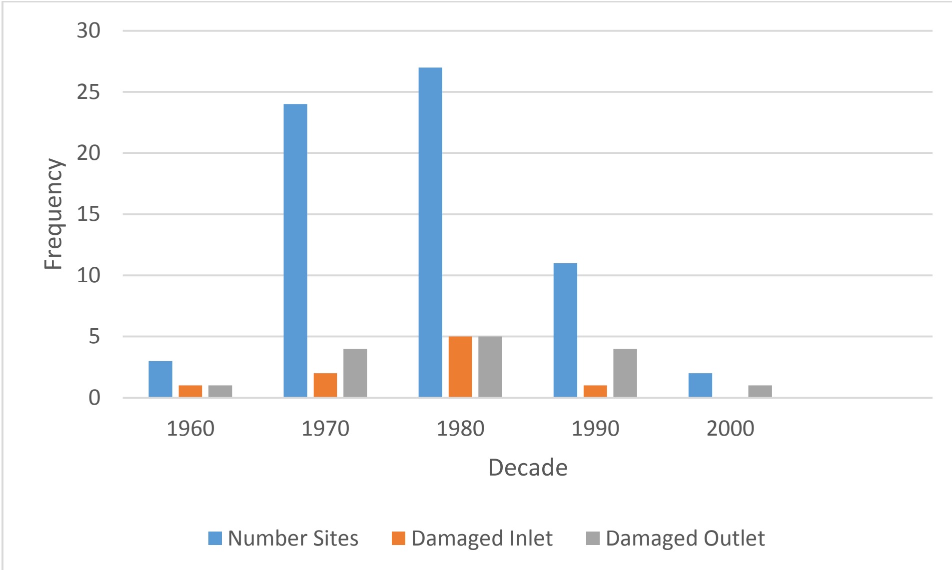
Table 4: Summary results of Hamilton Township Detention Basin Assessment.

Note: Percentages in parentheses represent percent of decade cohort, not total sites.

	No. Obs	Percent of Total Sites	1960s	1970s	1980s	1990s	2000s
Number Sites: 67 total			**3**	**24**	**27**	**11**	**2**
GENERAL OBSERVATIONS:							
Any reports on the basin not functioning?	**2**	***3%***	0	0	0	2 (18%)	0
Are there any unauthorized or malfunctioning structures in the basin?	**2**	***3%***	0	1 (4%)	1 (4%)	0	0
Are there concrete low flow channels. Is the water entering the basin directly exiting the basin outlet without coming in contact with the basin bottom soil and vegetation?	**37**	***55%***	3 (100%)	8 (33%)	18 (67%)	6 (55%)	2 (100%)
Is there standing water or evidence of standing water in the basin?	**17**	***25%***	1 (33%)	7 (29%)	7 (26%)	1 (9%)	1 (50%)
INLET:							
Signs of breakage, damage, corrosion, or rusting of inlet structure/pipe?	**9**	***13 %***	1 (33%)	2 (8%)	5 (19%)	1 (9%)	0
Debris or sediment accumulation in or around the inlet clogging the inlet opening/pipe?	**27**	***40%***	1 (33%)	12 (50%)	11 (41%)	2 (18%)	1 (50%)
Signs of erosion, scour or gullies; rock or vegetation above or around the inlet structure?	**11**	***16%***	0	4 (17%)	7 (26%)	0	0
Tree roots, woody vegetation growing close to or through the inlet structure or a situation impacting the structure's integrity	**10**	***15%***	0	3 (13%)	6 (22%)	1 (9%)	0
BASIN:							
Accumulation of debris or litter within basin?	**11**	***16 %***	0	4 (17%)	5 (19%)	2 (18%)	0

	No. Obs	Percent of Total Sites	1960s	1970s	1980s	1990s	2000s
Exposed dirt or earth visible, are there areas without vegetation or where turf is damaged?	**7**	***10%***	0	3 (13%)	4 (15%)	0	0
Excess sediment accumulation in the basin?	**28**	***42%***	1 (33%)	11 (46%)	12 (44%)	4 (36%)	0
Basin wall/embankment eroded, slumping caved or being undermined?	**2**	***3%***	0	2 (8%)	0	0	0
OUTLET:							
Breakage, damage, corrosion or rusting to outlet pipe or conveyance?	**15**	***22%***	1 (33%)	4 (17%)	5 (19%)	4 (36%)	1 (50%)
Signs of erosion, scour or gullies; rock or vegetation above or around the outlet structure?	**11**	***16%***	0	6 (25%)	3 (11%)	1 (9%)	1 (50%)
Debris or sediment accumulation in or around the outlet pipe (i.e. debris or sediment)?	**41**	***61%***	3 (100%)	16 (67%)	14 (52%)	7 (64%)	1 (50%)
Accumulation of debris or litter in or around outlet?	**24**	***36%***	2 (67%)	8 (33%)	8 (30%)	5 (45%)	1 (50%)
Tree roots or woody vegetation impacting the outlet or causing potential damage to the structure?	**12**	***18%***	0	6 (25%)	3 (11%)	3 (27%)	0
OTHER:							
Are pipes, conduits, or conveyances free of debris, clogs and in good condition?	**2**	***3%***	0	1 (4%)	0	1 (9%)	0
Large tree or root growth close to pipes or conveyances with the potential to crack structure or impeded flow?	**1**	***1%***	0	1 (4%)	0	0	0
Signs of erosion, scour or gullies; rock or vegetation at or down slope of the outfall?	**2**	***3%***	0	1 (4%)	1 (4%)	0	0

Figure 6: Frequency of inlet and outlet damage in Hamilton Basins by decade.



DISCUSSION

The assessments identify three classes of problems: accumulation of material, structural deterioration, and erosion. Material accumulation is primarily a maintenance issue since sediment, plant debris, and litter can all be removed from the basin. Livingston et al. (1997) recommends monthly inspections of detention basins to check for and address clogging. When systems contain a forebay, USEPA (2012c) recommends removing sediment from it every 5 to 7 years. Lack of correlation between material accumulation and basin age (Figure 3) is not unexpected since accumulation is a correctable problem. Both property owner maintenance, basin design, and land use are all possible explanations for variations in material accumulation.

A chi-square test did find associations between the presence of sediment and debris around the outlet and standing water in the basin which suggests that material accumulation at the outlet contributes to clogging and poor system drainage. It is also reasonable to assume that sediment clogging in inlets may cause water to back up in storm drains causing nuisance flooding. In several of the basins accumulated sediment was colonized by plants which keeps the sediment in place, both near the inlet and outlet. On the one hand, this improves the sediment trap efficiency of the basin by preventing a subsequent storm from washing out the sediment. But on the other hand the accumulated plants and soil can contribute to clogging and in severe cases basin volume loss. In a study of an 18 year old detention basin, Guo (1997) found that the basin accumulated approximately 0.8 cm of sediment per year which significantly decreased the its flood control capacity. Sediment accumulation should be carefully monitored to prevent loss of basin function.

Both the Middlesex County and Hamilton studies do not support the initial hypothesis that the condition of inlet and outlet structures would be worse in older detention basins compared to younger sites. In the larger Hamilton study, damage to inlets and outlets was not very common; the frequency and percentage data do not show any age based pattern. A chi-square test of association could not be performed to compare the occurrence of inlet and outlet damage in the Hamilton group since the expected values were less than 5. Of the 21 Hamilton basins with damage to the inlet and/or outlet, only 3 had both conditions in common. One could expect that if age were an important factor in the condition of a basins' structures, that damage would appear concurrently in inlets and outlets.

The 2004 cohort of Middlesex County sites illustrate the variation in concrete condition that is independent of age (Figure 2). H04A's outlet received a concrete score of 3 for 25 to 50% damage yet the inlets and outlets its companion basin, H04B, all scored 1 on the concrete ranking. PI03 had inlets with the worst damage, 2 of its 3 inlets receiving a score of 3. The most damaged outlet in the Middlesex study (ED10) is also the second oldest site in the study, though inlets and outlets of the youngest basin (H22) already exhibit a small amount of damage. Despite the poor condition of some of the study's concrete structures, the damage appears to all be superficial and not inhibiting basin function. One potential problem that could stem from concrete deterioration is the accumulation of concrete aggregate in the outlet piping which could reduce hydraulic capacity.

The majority of the structural components of the basins in the two surveys are made of concrete. The U.S. Army Corps of Engineers (1998) recommends assuming concrete pipes have a service life of 70 to 100 years. While there are many causes of concrete deterioration, the corrosion of embedded rebar and freezing and thawing are probably the most relevant to detention basin components. Rebar corrosion is the most frequent cause of damage to concrete and results from the presence of chloride in water (usually from de-icers) creating an electrolytic cell in the concrete structure which degrades the metal reinforcements and the surrounding concrete. Concrete exposed to fluctuating water levels is vulnerable to damage from freeze thaw when water saturates the concrete pores then expands to cause the concrete to disintegrate. Additionally poor manufacturing can result in concrete structures more prone to deterioration. Minimizing the exposure of components to standing water and using properly made concrete products is probably the best preventative measures that can be taken to prolong the life of detention basin components (USACE 1995).

Erosion is problematic in detention basins for two primary reasons. The loosened sediment can be exported from the basin, counteracting the basin's ability to reduce sediment loads, and erosion can lead to instability in the earthen dams used to create the basin (Livingston et al. 1997). Erosion rates around inlets and outlets in the Hamilton study were both 16%. While inlet and outlet erosion occurred at the same rates, only 4 out of 18 sites had both conditions at the same time. A chi-square test could not be run on these two conditions since expected values were less than 5. The Hamilton erosion rates are comparable to a study by Lindsey et al. (1992a) which found 22% of 116 dry basins with erosion around the intake or outfall. Maintaining healthy vegetation and using energy dissipaters at the opening of inlets can help prevent erosion from occurring (Livingston et al. 1997).

CONCLUSION

Data from both the Middlesex and Hamilton cohorts could not disprove the null hypothesis that there is no difference between the conditions of newer and older detention basins. Lack of balance in the study design may have contributed in the data's inability to reject the null hypothesis. However other factors such as the initial quality of concrete structures, basin design, property owner maintenance, and adjacent land use could all have also contributed to variation in basin conditions. The significant correlation between the presence of outlet sediment and debris with ponded water emphasizes the importance of keep outlet structure clear in order to prevent nuisance ponding. Sedimentation in all parts of the basin – inlets, channels, and outlets – is a prevalent condition but is correctable with periodic maintenance. The study suggests that by installing well-made structural products and regular maintenance, detention basins can remain in decent condition for over 30 years.

Chapter 5: The Biodiversity and Ecological Functions of Naturalized Detention Basins

INTRODUCTION

Typical dry detention basins provide a moderate degree of pollutant removal through sedimentation, though these removal rates are highly dependent on drawdown time. Without a permanent pool, detention basins are limited in their capacity to remove soluble pollutants such as nitrate (USEPA 2012c). Naturalization is a retrofitting process aimed at enhancing the water quality treatment performance of existing stormwater detention basins. Lev (1998) describes a naturalization project in Oregon as "converting a 0.6070 Ha grass bowl with a concrete trench into a meandering stream surrounded by native plants." The rationale behind replacing conventional turf with alternate vegetation is to increase the infiltration of stormwater and uptake of pollutants, improve aesthetics, cool water temperatures, reduce flow velocity, and decrease maintenance (JRBP 2004, Flakne and Keller 2012, StormwaterPA 2012).

Extended detention basins, a subset of detention basins, are initially designed to enhance water quality treatment and infiltration. While the definition of extended detention basin is somewhat variable, the ability of a basin to hold water for a prolonged period of times (usually more than a day) before drying out is a repeated theme. Other common features that separate naturalized or extended basins from conventional basins can include sediment forebays, lack of low flow channels, non-turf vegetation, wetland marsh type areas, and small ponds, also referred to as "micropools" (PADEP 2006, Blick et al. 2004, NCDWQ 2009, UDFCD 2010, VADCR 1999, IDT 2011). Forebays are a type of pre-treatment structure located at the mouth of basin inlets while micropools are small ponds of water often dug in front of the outlet. Both are intended to improve sediment capture; a forebay tends to trap coarser sediment and debris while micropools provide longer detention time to settle finer particulate matter (Blick et al. 2004, Guo et al. 2012). Removing concrete low flow channels and using non-turf or wetland vegetation can increase stormwater contact time with the basin bottom, allowing pollutant removal to occur through physical filtration, absorption, and plant uptake (VADCR 1999).

For the purposes of this study, detention basins that contain non-turf vegetation will be referred to as naturalized basins. The study does not distinguish between basins that were originally designed for wetland plants, retrofitted basins, or basins spontaneously colonized by different plant species. Additionally, the study uses the word urban in its general sense to describe areas that have been significantly altered from their natural state through the addition of impervious surfaces to the landscape.

Naturalized detention basins can have several potential drawbacks. Lack of a low flow channel can result in short circuiting, where water cuts the shortest path between the inlet and outlet, limiting the effectiveness of water quality treatment (Douglass County 2006). Decaying plant material could export nutrients from the basin (Applied Ecological Services 2008). This may be the case in a study by Bartone and Uchrin (1999) which found a basin with newly planted wetland species exported a higher mass of pollutants including total suspended solids, nitrogen, and phosphorus. It is worth noting that two of the study samples were taken in November and December when plants were presumably dormant. This suggests the possibility the basin effectiveness may also be limited by season. Plant growth has the potential to exacerbate clogging, both by trapping material in front of inlets and by blocking orifices on the outlet structure (Douglas County Colorado 2006**,** NCDWQ 2009). However clogging is a problem in conventional basins as well. Water retained in the basin soil can create soggy conditions prohibiting access by maintenance vehicles (NCDWQ 2009).

Many guidance documents about naturalized basins as well as other stormwater systems emphasize that only native plant species should be planted in the basins (PADEP 2006, JRBP 2004, Applied Ecological Services 2008, Douglas County 2006, Flakne and Keller 2012, Blick et al. 2004). Preferences for native (or indigenous) plants stem out of a concern that non-native species will replace native biota. This replacement could potentially alter ecosystem processes such as nutrient-cycling and in extreme cases contribute to higher extinction rates (Vitousek et al. 1997, Pimm et al. 1995). However when considering urbanized environments, Del Tredici 2010 believes non-native plant species should not be vilified, but rather accepted for their ability to occupy an ecological niche in a highly disturbed landscape. One study of plant biota at wetland mitigation sites, which bare similar characteristics to naturalized detention basins, have found that after 4 to 21 years 17.8% of surveyed species were non-native (Balcombe et al. 2005). Previously disturbed riparian wetlands in the West Midlands Conurbation, UK tended to have higher amounts of non-native species compared to undisturbed sites (Maskell et al. 2006). Leck and Leck (1991) found that non-natives accounted for 27% of total flora in a study of constructed and reference wetlands along the Delaware River. Given the colonization of non-native plant species in human influenced wetland environments, despite the intentions of landscaping plans these species should also be expected to colonize naturalized detention basins as well.

The plants growing in naturalized basins may do more than improve the performance of the system. While naturalized detention basins are manmade and often exist in urbanized environments, they nevertheless contain a collective of living organisms which have the ability to provide ecosystem services that are of value to humans. Costanza et al. (1997) defines ecosystem services as properties or processes of an ecosystem which provide benefits to humans. Ecosystem services are also referred to as ecosystem functions in other applications. The phrase ecosystem capital refers to the ecosystems themselves in the context of the services they provide. A report by the President’s Council of Advisors on Science and Technology (2011) recommends the U.S. government to take steps to protect the country's environmental capital in order to slow and halt a trend of ecosystem degradation.

Interestingly, almost all references to the urban environment in the PCAST Report are related to the negative effects of urbanization on ecosystems and biodiversity. The exception is a reference to a U.S. Forest Service report on the ecosystem services provided by urban trees. Yet Kowarik (2011) argues urban ecosystems have the ability to provide ecosystem services and social benefits, such as contributing to biodiversity conservation. Del Tredici (2010) takes a similar stance and suggests that given the increasing trend of urbanization, it is worthwhile to more actively manage the urban plant communities to maximize their environmental services. Bolund and Hunhammar (1999) identified ecosystem services provided by ecosystems in Stockholm, Sweden: air filtration, micro climate regulation, noise reduction, rainwater drainage, sewage treatment, and recreation and cultural values. One of the steps to protect environmental capital recommended by PCAST entails documenting the current condition of U.S. ecosystems and the services they provide. Urban ecosystems, including naturalized detention basins and other stormwater management systems that incorporate plants into their designs, should not be excluded from such a census.

The previous projects in this study investigated the effect of time on the physical and structural components of stormwater detention basins. The purpose of this project is to investigate how the plant communities in naturalized basins may change with time and how these plants can affect the ability of the basin to temporarily detain water and remove pollutants, its primary functions. By identifying the plant species in naturalized basins, measuring species abundance, and assessing the condition of the basin, this project specifically addresses the following the questions:

1. What species become abundant in naturalized basins as they age, how does diversity change, and what is the prevalence of non-indigenous and invasive species?
2. How does the presence of non-turf vegetation effect the function of naturalized basins?
3. What are the potential ecosystem services that a naturalized basin could provide?

METHODS
Site Location

The study measured plant communities in eleven naturalized detention basins in Middlesex County, New Jersey; the age, size, and adjacent land use of each are provided in Table 1. Two of the basins are located in predominantly residential areas while the remaining nine are sited in traffic islands along the side of highways. Site H04 contains two basins in series, with basin A flowing into B. All of the basins have multi-stage outlets with the exception of H04A which has a culvert type outlet that feeds in H04B.

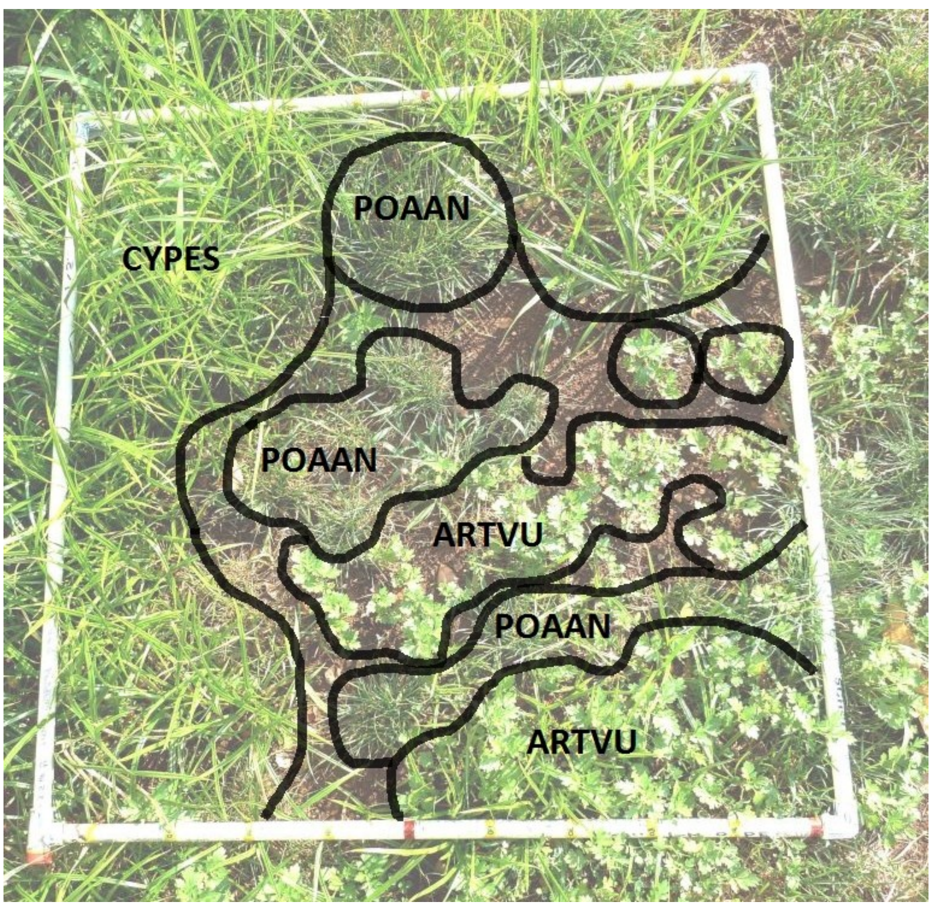
Table 1: Naturalized detention basin study site description

Site ID	Installation Year	Size (acres)	Adjacent Land Use
H01	2007	0.49	Highway
H02	2007	0.76	Highway
H03	2009	0.48	Highway
H04A	2004	0.16	Highway
H04B	2004	0.36	Highway
H08	2007	0.40	Highway
H17	2006	0.28	Highway
H21	2004	0.42	Highway
H22	2011	0.26	Highway
NE01	1996	0.61	Park, Residential
NO02	1991	0.27	Residential

Plant Community Sampling

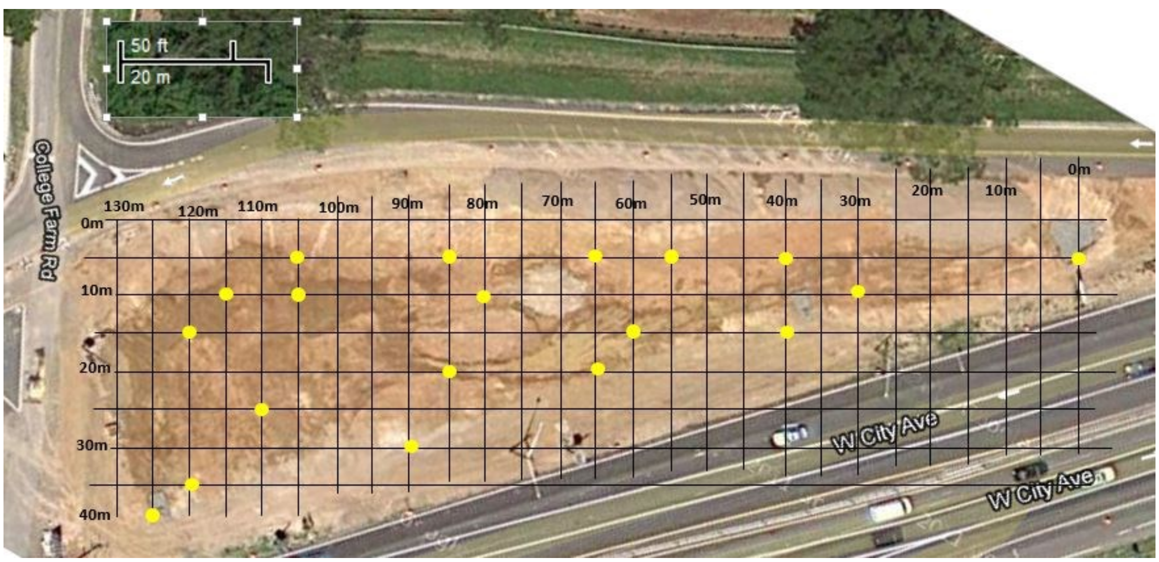
Vegetation sampling was conducted from June to October 2012. Preliminary site visits showed that the basins predominantly contained forbes and grasses so a quadrat sampling method was chosen to measure vegetation cover by species at each site (Brower et al. 1990). Quadrat sampling involved placing a 1m x 1m square of PVC pipe on the ground at predetermined random locations in the basin. At each location, all of the plant species in the square were identified and the percent of the square covered by each species was visually estimated; an example of this method is shown in Figure 1. When a species could not be identified in the field, a piece of the plant was placed in a labeled bag and identified in the lab. Each spot where the square was used to measure vegetation is a sample unit.

Figure 1: Example Sample Unit plant cover assessment. (Letters represent species code used by plants.usda.gov)



At each basin the location of the sample units were randomly determined by drawing a grid over an aerial photo of the site and assigning each intersection of the grid a number (see example in Figure 2). A random number generator provided a list of numbers which was used to select points on the grid to be the sample unit locations. During the site visit, measuring tapes were used to mark the location of the pre-assigned sample unit points. Each site had 15 to 20 sample units, in proportion to the size of the basin and the numbers of plant species found. At some sites, sampling would end when no new species appeared in the sample units. In addition to noting the species and cover within each square, the sample unit's position within the basin was also recorded as either bottom, if it was on the floor of the basin, or slope, if it was on the basin's side wall.

Figure 2: Example random sampling plan for H22.



Plant species were classes as indigenous (native) or non-indigenous according to its profile on the United States Department of Agriculture's Plants Database website (USDA 2013). The Plants Database also provided the wetland indicator status for each plant. Table 2 contains a description of each status. Thompson et al. (1995) suggests that categorizing plant species based on their invasiveness instead of native status is a more informative practice since invasive plants share more common traits regardless of their origin. Invasiveness classification was based on the Plants Database (USDA 2013) and the U.S. Forest Service's (2013) Eastern Region Invasive Plants List (plants labels as Category 1 or 2 on this list were labeled as invasive for this study).

Table 2: Wetland Indicator Status codes (Lichvar and Minkin 2008).

CODE	Name	Description
OBL	Obligate wetland plants	>99% occurrence in wetlands
FACW	Facultative wetland plants	Between 67 and 99% occurrence in wetlands
FAC	Facultative plants	Between 33 to 66% occurrence in wetlands
FACU	Facultative upland plants	Between 1 and 32% occurrence in wetlands
UPL	Upland plants	<1% occurrence in wetlands
NR	Not reported	Status not reported in plants.usda.gov database

Calculations

Richness (S) is a count of the number of species in a particular area. Plant species richness was calculated at each site, for each position (slope and bottom) within each site, and for all eleven sites aggregated together. Richness is a fairly simple way to describe a community, it provides no information about the distribution and dominance of the different community members (Smith and Smith 2001).

The advantage of using 1 m^2 sample units is that the percent cover (e.g. 80%) of a particular species is easily converted into the area of cover for that species (e.g. 0.8 m^2). To characterize the abundance of different species in the study, cover area was used to calculate relative dominance (RD) (Smith and Smith 2001):

$$RD = \frac{coverage\ of\ species\ i}{total\ coverage\ of\ all\ species} \times 100 \qquad (1)$$

RD is reported as a percentage. One drawback of using relative dominance in this study is that it favors larger plants that cover more area by virtue of their size. Relative dominance was calculated for each species by site and by position within each site.

Measures of diversity account for both the number of species in a study area as well as the evenness of their distribution. While there are several diversity metrics, the Shannon Index (H') was chosen for this study for several reasons. This index does not favor extremely prevalent or rare species, it is appropriate to use on random samples which represent a larger community (McCune and Grace 2002), and it has been used in similar studies of wetland plant communities (Moser et al. 2007, Kellogg and Bridgham 2002, Thompson et al. 2007). The Shannon Index (H') is calculated using the following equation:

$$H' = -\sum_{i=1}^{S}(p_i)\ln(p_i) \qquad (2)$$

Where S is the number of species and p_i is the proportion of cover occupied by species i (Smith and Smith 2002). In this study, RD was used as p_i. H' was calculated for each site and for each position within each site. A Krushkal-Wallace test was used to compare H' between the two landscape positions since H' was not normally distributed. All statistical tests were done using R statistical software.

Basin Condition Assessment

An assessment protocol developed by the Rutgers Water Resources Extension Group was used to evaluate the potential effects of naturalization on the condition and function of the detention basins. The assessment is a yes or no questionnaire based on a visual inspection of the basin and its components; it is described in greater detail in Chapter 4. Assessments of the naturalized basins were conducted in April and May of 2013 when most of the vegetation was still dormant which facilitated inspection of the sites.

RESULTS

The study identified 119 plant species in the 11 naturalized basin sites. This count includes two unidentified members of the *Asteraceae* family and several unidentified samples from the *Poaceae* family. Unknown *Poaceae* samples were grouped under a common POA label instead of treated separately so as not to overestimate species richness. It was not possible to determine which species the samples from the *Typha* genus belonged to, so they are presented under a generic *Typha spp.* label. The complete species list is provided in Appendix D.

Table 3 lists the 13 most abundant species from an aggregate of all of the study sites based on RD. The cutoff at *Lythrum salicaria* for the list is based on the mean of the cover area for all species plus one standard deviation. In combination, unidentified members of the *Poaceae* family represent the most common type of plant. However in reality this group probably represents several different species which means *Artemesia vulgaris* is the most abundant species.

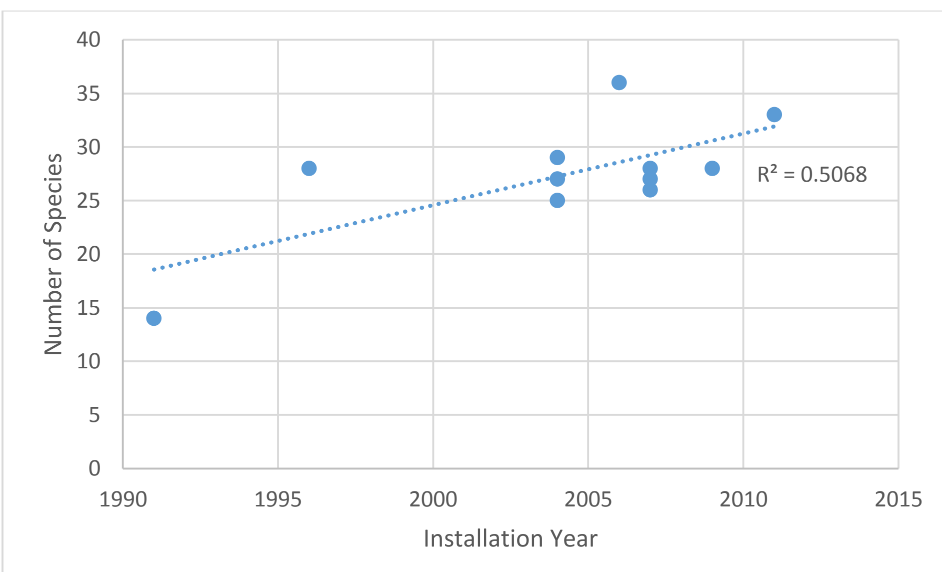
Table 3: Most abundant species from an aggregate of the eleven study sites. RD = relative dominance.

Species	RD	Wetland Indicator	Invasive?	Indigenous?
Unidentified poaceae	13.6%	Unknown	Unknown	Unknown
Artemesia vulgaris	7.8%	UPL	Noninvasive	Nonindigenous
Leersia oryzoides	5.1%	OBL	Noninvasive	Indigenous
Phragmites australis	4.7%	FACW	Invasive	Nonindigenous
Typha spp.	4.2%	OBL	Invasive	Indigenous
Coronilla varia	3.6%	Unknown	Invasive	Nonindigenous
Echinochloa crusgalli	3.5%	FAC	Noninvasive	Nonindigenous
Persicaria hydropieroides	3.5%	OBL	Noninvasive	Indigenous
Eleocharis obtusa	3.1%	OBL	Noninvasive	Indigenous
Lotus corniculatus	3.1%	FACU	Noninvasive	Nonindigenous
Persicaria pensylvanica	3.0%	FACW	Noninvasive	Indigenous
Juncus effuses	2.7%	OBL	Noninvasive	Indigenous
Lythrum salicaria	2.6%	OBL	Invasive	Nonindigenous

In contrast to the most dominant species, 34 of the 119 total species (29%) had a total percent cover value less than 0.1% of the total sampled plant cover. Of the entire species list, *Calla palustris* (0.03% of total cover) is the only species identified as rare in the State of New Jersey (NJDEP 2010).

Appendix E contains the four species with the highest cover at each site and the site's corresponding Shannon Index (H'). Here, RD is the proportion of the particular species' cover at site x to the total species cover at that site. Unidentified *Poaceae* appears 5 times in the top 4 while *Phragmites australis* appears 4 times on the list. Out of the 11 sites, no single species represents more than half of a site's cover; *Typha spp.* has the highest proportion of cover at a single site (0.46 at H04A). H01 has the highest species richness (26), NO02 has the lowest (9). While NO02 is the oldest site and H01 is one of the younger basins, Figure 2 shows that the trend of decreasing species richness with increasing age is somewhat weak. It is not possible to determine from the study if the decrease in H' is a factor of time or design.

Figure 3: Species richness of entire basin as a function of installation year.



Figures 4 and 5 show the distribution of species at each site based on classifications as indigenous/nonindigenous and invasive/noninvasive. The distribution in Figure 4 is based on the number of species (richness) at each site while Figure 5 is based on the relative dominance for each species. With the species richness distribution (Figure 4), the proportion of indigenous and nonindigenous species is relatively consistent in all of the sites built after 2000. However when relative dominance is accounted for there is greater variation with some sites dominated by nonindigenous species and others by indigenous (Figure 5). Overall, noninvasives are more abundant and represent a higher percent of the species, this reflects the general prevalence of noninvasive in the dataset – 100 species are classed as noninvasive.

Figure 4: Distribution of invasive/noninvasive, indigenous/nonindigenous species as a percentage of total number of species per site.

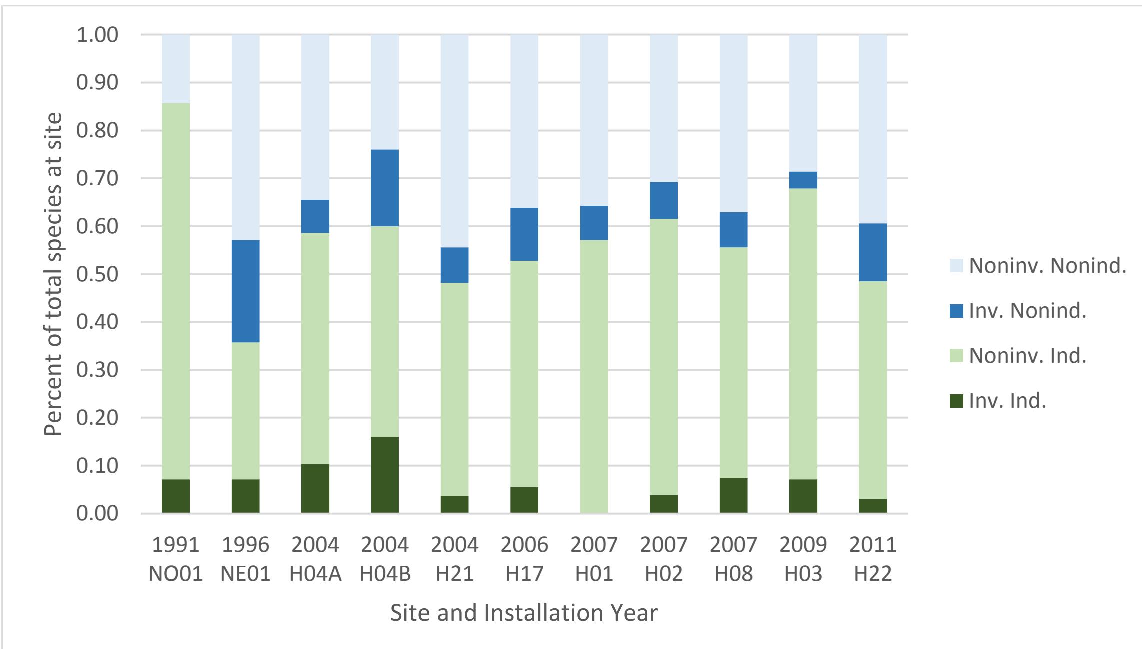


Figure 5: Distribution of invasive/noninvasive, indigenous/nonindigenous based on relative dominance (calculated from cover).

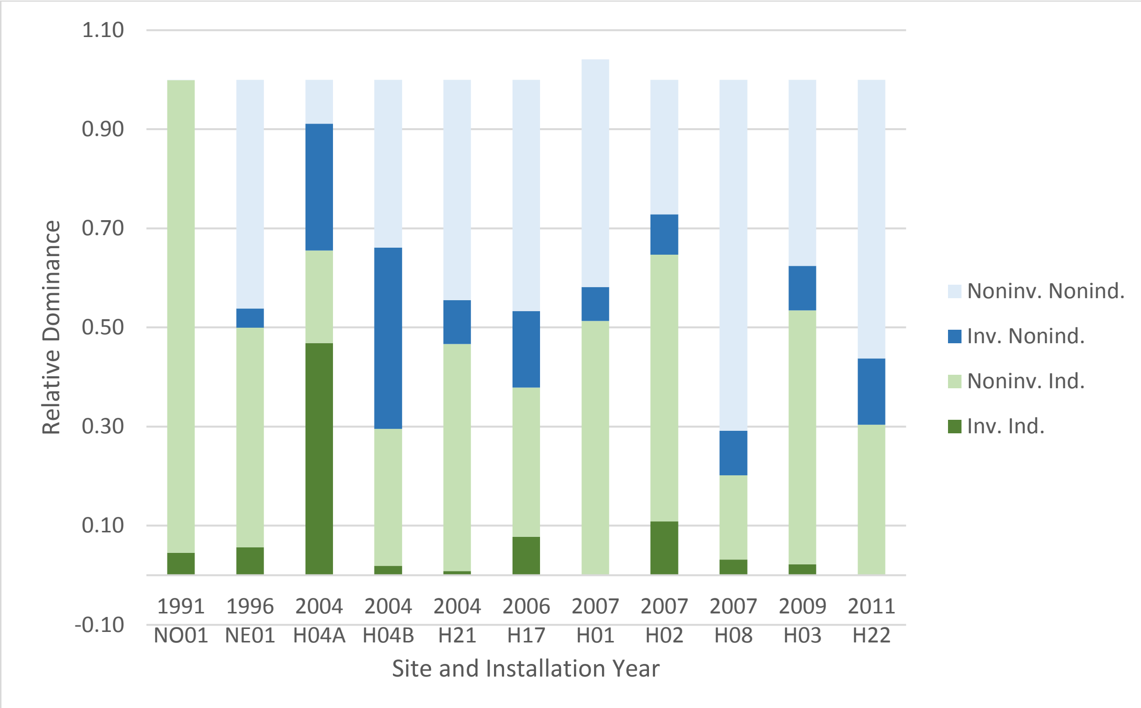


Figure 6 shows the distribution of species at each site based on their wetland indicator status (WIS); the distribution in Figure 7 is based on relative dominance. This study assumes that if no WIS is reported for a species, it is likely a facultative upland or upland species. According to the U.S. Army Corps of Engineers (USACE) Wetland Delineation guidelines, 50% of the vegetation in a wetland should have an OBL, FACW, or FAC classification (USACE 1987). Figure 6 shows that six of the eleven sites meet the USACE's wetland vegetation criteria. According to the USACE system vegetation is one of three criteria used to determine if an area is a wetland.

Vegetation results were also grouped based on the position of the sample unit within the basin – whether the sample was taken on the slope (or side wall) or on the bottom. As Table 4 and Figures 8 to 11 show, the plant communities differ in their composition and dominance when grouped in this manner. Overall, samples in the slope position are dominated by upland and facultative upland species while the bottom samples are dominated by wetland obligate and facultative species. H01 and H02 are outliers in this respect by having obligates as dominant slope species. These two basins are fairly shallow compared to the rest of the study sites (meaning the distance between the basin bottom and rim is small) and fewer samples were taken on the slope which may explain the presence of wetland species there. While H01 is situated in a circular traffic island, its basin is irregularly shaped and contains a crescent shaped channel connecting the inlet and outlet. Splitting H01 samples by position may be inappropriate. There are also a few cases of upland or facultative upland species being dominant in bottom samples, including H08 (*L. corniculatus*), H01 (*A. vulgaris* and *S. oblongifolium*), H17 (*A. vulgaris*), and H21 (*S. pilosum*). Microtopography in the bottom probably provides areas elevated enough to allow the growth of these species.

Figure 6: Distribution of species based on wetland indicator status as a percentage of total number of species per site.

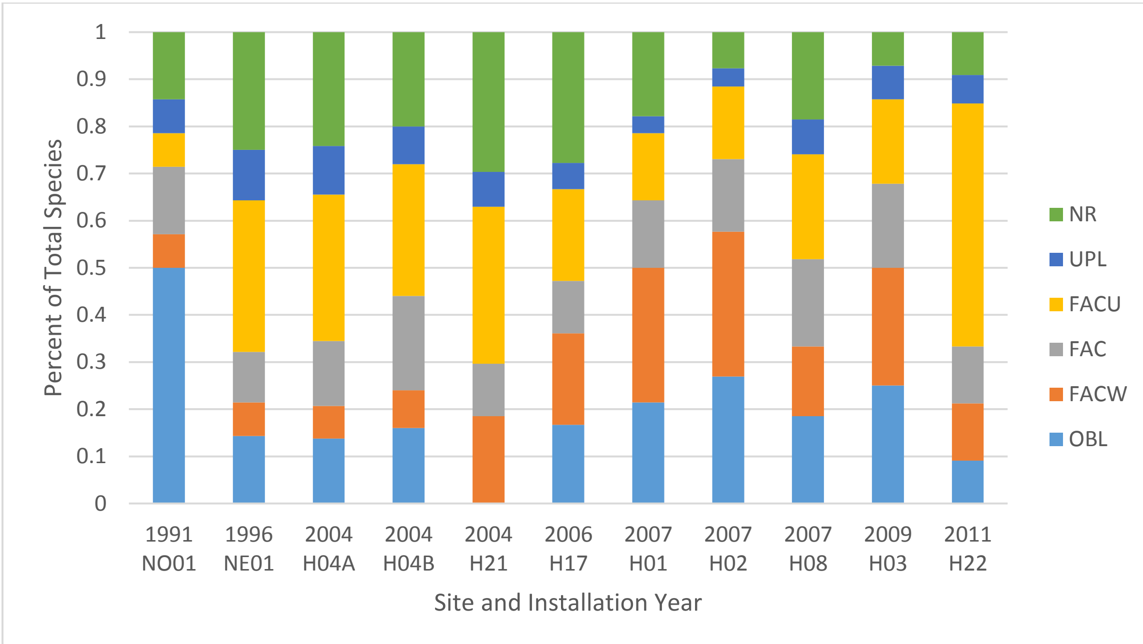


Figure 7: Distribution of species based on wetland indicator status based on relative dominance.

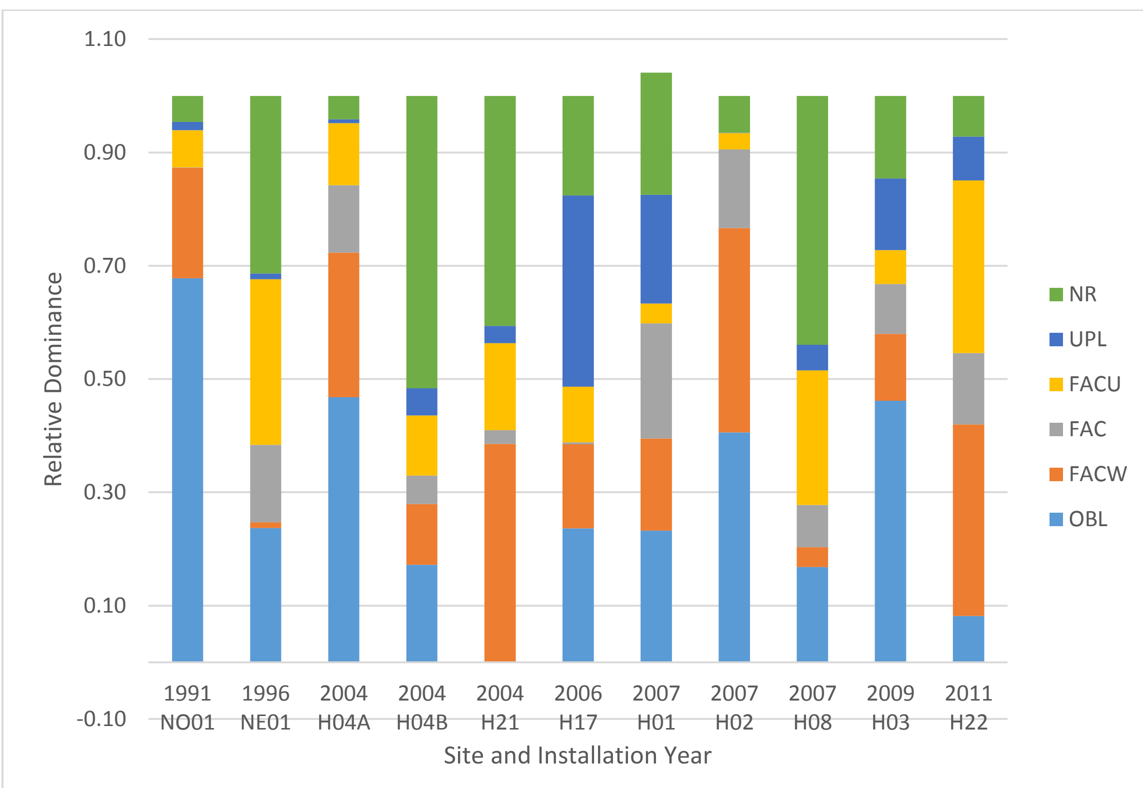


Table 4: Four most prevalent species by relative dominance (RD) at each detention basin.

Slope - Species	RD	WIS	Bottom - Species	RD	WIS
Site: H01					
Leersia oryzoides	0.17	OBL	*Artemesia vulgaris*	0.33	UPL
Echinochloa crusgalli	0.17	FAC	*Leersia oryzoides*	0.16	OBL
Artemesia vulgaris	0.09	UPL	*Calystegia silvatica*	0.16	NR
Symphytrichum oblongifolium	0.09	UPL	*Symphytrichum oblongifolium*	0.1	UPL
Site: H02					
Lythrum salicaria	0.25	OBL	*Bidens polylepsis*	0.15	FACW
Unknown poaceae	0.19	NR	*Typha spp.*	0.13	OBL
Bidens polylepsis	0.19	FACW	*Panicum dicchotomiflorum*	0.12	FACW
Eleocharis obtusa	0.1	OBL	*Echinochloa crusgalli*	0.10	FAC
Site: H03					
Artemesia vulgaris	0.29	UPL	*Eleocharis obtuse*	0.32	OBL
Unknown poaceae	0.24	NR	*Lythrum salicaria*	0.14	OBL
Persicaria pennsylvanica	0.13	FACW	*Juncus effuses*	0.09	OBL
Lotus corniculatus	0.12	FACU	*Unknown poaceae*	0.08	NR
Site: H04A					
Liquidambar styraciflua	0.19	FAC	*Typha spp.*	0.59	OBL
Potentilla simplex	0.15	FACU	*Phragmites australis*	0.39	FACW
Setaria lutescens	0.11	FAC	*Phalaris arundinacea*	0.01	FACW
Symphyotrichum dumosum	0.07	NR	*Lythrum salicaria*	0.01	OBL
Site: H04B					
Coronilla varia	0.50	NR	*Phragmites australis*	0.21	FACW
Unknown poaceae	0.34	NR	*Unknown poaceae*	0.15	NR
Barbarea vulgaris	0.04	FAC	*Persicaria hydropiperoides*	0.14	OBL
Persicaria hydropiperoides	0.03	OBL	*Polygonum sagittatum*	0.11	OBL
Site: H08					
Unknown poaceae	0.32	NR	*Unknown poaceae*	0.32	NR
Lotus corniculatus	0.20	FACU	*Lythrum salicaria*	0.18	OBL
Plantago lanceolata	0.13	FACU	*Lotus corniculatus*	0.08	FACU

Slope - Species	RD	WIS	Bottom - Species	RD	WIS
Setaria viridis	0.12	NR	*Carex lurida*	0.07	OBL
Site: H17					
Artemesia vulgaris	0.48	UPL	*Artemesia vulgaris*	0.22	UPL
Setaria viridis	0.07	NR	*Phragmites australis*	0.17	FACW
Coronilla varia	0.07	NR	*Schoenoplectus pungens*	0.14	OBL
Cornus sericea	0.06	NR	*Persicaria hydropiperoides*	0.10	OBL
Site: H21					
Unknown poaceae	0.48	NR	*Persicaria pennsylvanica*	0.53	FACW
Phragmites australis	0.09	FACW	*Cyperus esculentus*	0.34	FACW
Lotus corniculatus	0.06	FACU	*Symphyotrichum pilosum*	0.07	FACU
Calystegia silvatica	0.06	NR	*Echinochloa crusgalli*	0.03	FAC
Site: NE01					
Unknown poaceae	0.55	NR	*Euthamia graminifolia*	0.21	FAC
Plantago lanceolata	0.15	FACU	*Juncus effuses*	0.20	OBL
Oxalis stricta	0.12	FACU	*Leersia oryzoides*	0.20	OBL
Lotus corniculatus	0.08	FACU	*Unknown poaceae*	0.10	NR
Site: NO02					
Impatiens capensis	0.36	FACW	*Leersia oryzoides*	0.39	OBL
Symphyotrchum pilosum	0.18	FACU	*Persicaria hydropiperoides*	0.28	OBL
Calystegia silvatica	0.18	NR	*Impatiens capensis*	0.14	FACW
Carex vulpinoidea	0.13	OBL	*Typha spp.*	0.06	OBL

Figure 8: Distribution of species based on invasive/noninvasive, indigenous/nonindigenous status by relative dominance on the slope of each site.

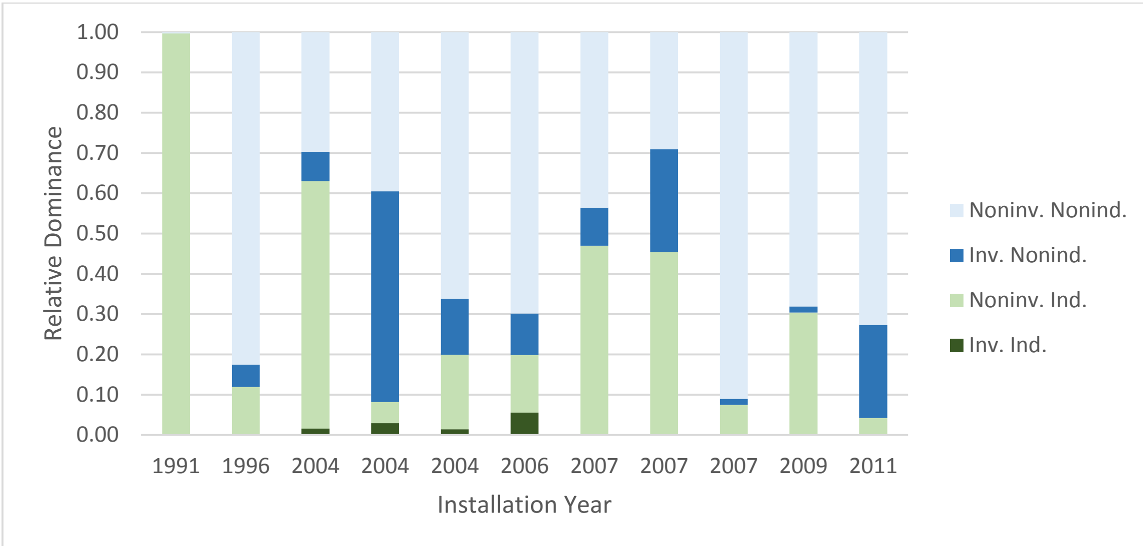


Figure 9: Distribution of species based on invasive/noninvasive, indigenous/nonindigenous status by relative dominance on the bottom of each site.

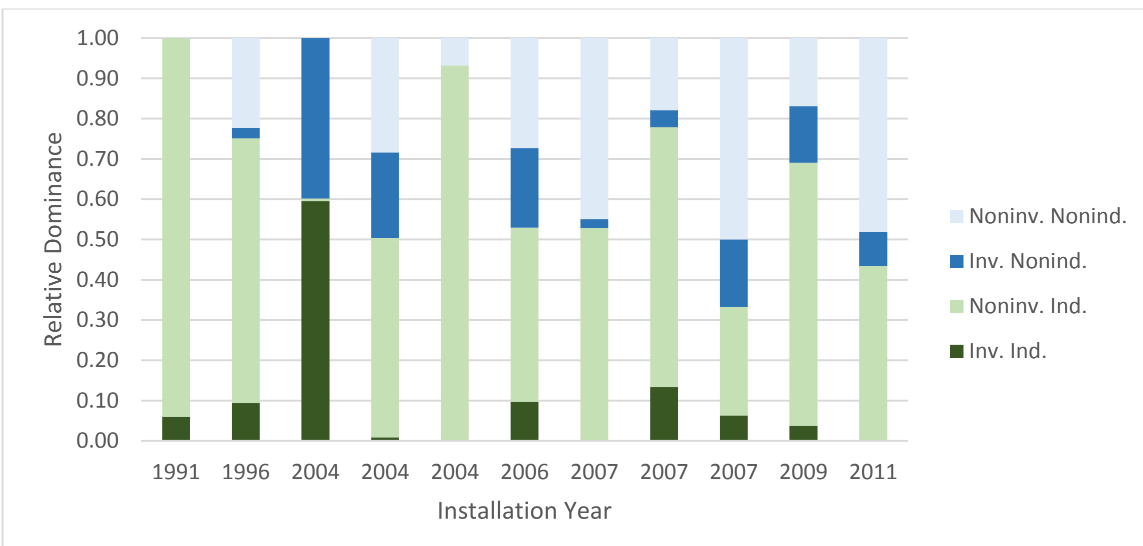


Figure 10: Distribution of species based on wetland indicator status by relative dominance on the slope of each site.

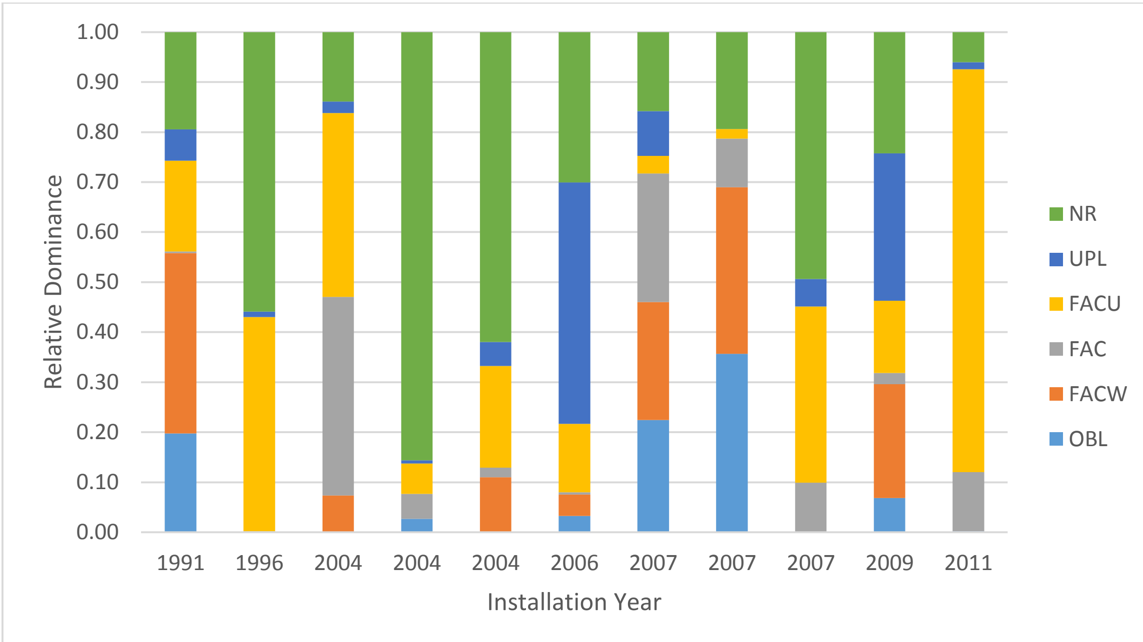
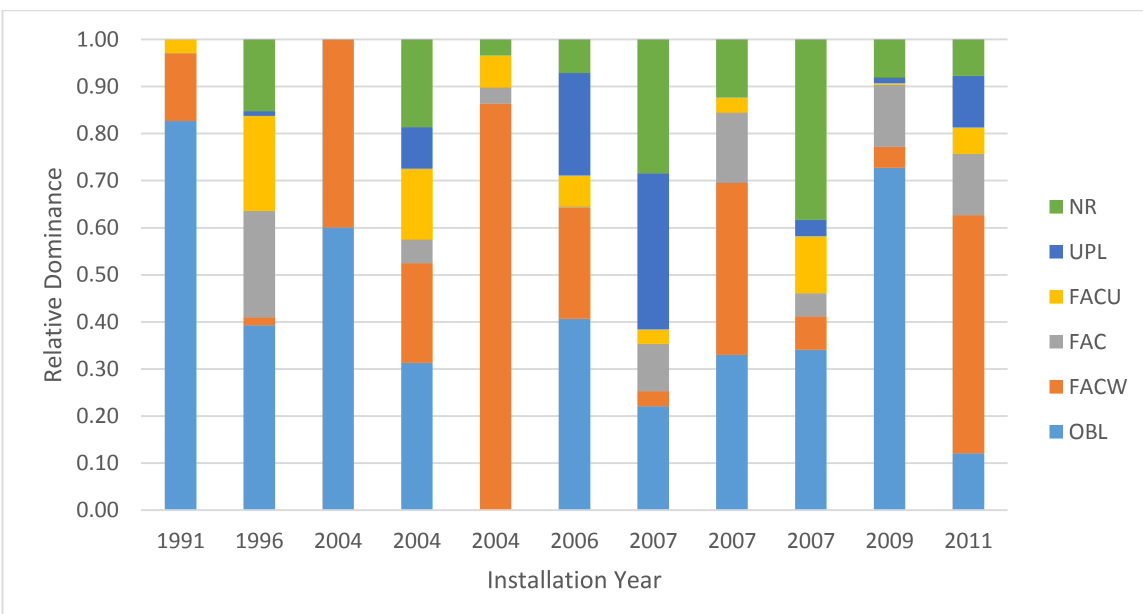


Figure 11: Distribution of species based on wetland indicator status as a percentage of area cover on the bottom of each site.



Unidentified *Poaceae* species were the most frequent dominant species in both the slope and bottom samples, with *A. vulgaris* and *L. corniculatus* appearing on multiple slope lists as well. *L. oryzoides*, *L. salicaria*, *P. australis*, *P. hydropiperoides*, and *Typha spp.* all appear on multiple bottom lists. *Typha spp.*, *C. varia*, *A. vulgaris*, *P. pennsylvanica,* and unidentified *Poaceae* all have RD values around 50% of their respective sites and position.

While different community types become established on the bottom and slopes of the basin, position seems to have little effect on the diversity of the plant communities. There is a weak correlation ($r^2 = 0.45$) between basin installation year and Shannon Index (H'); plant community diversity appears to decrease as sites age (Figure 12). The correlation between age and H' is even weaker when H' is calculated based on sample position at each site, as shown in Figure 13. A Kruskall-Wallace test of H' using position (slope or bottom) as a variable does not disprove the null hypothesis of no difference between the two groups ($p < 0.05$).

Figure 12: Shannon Diversity Index (H') as a function of basin installation year.

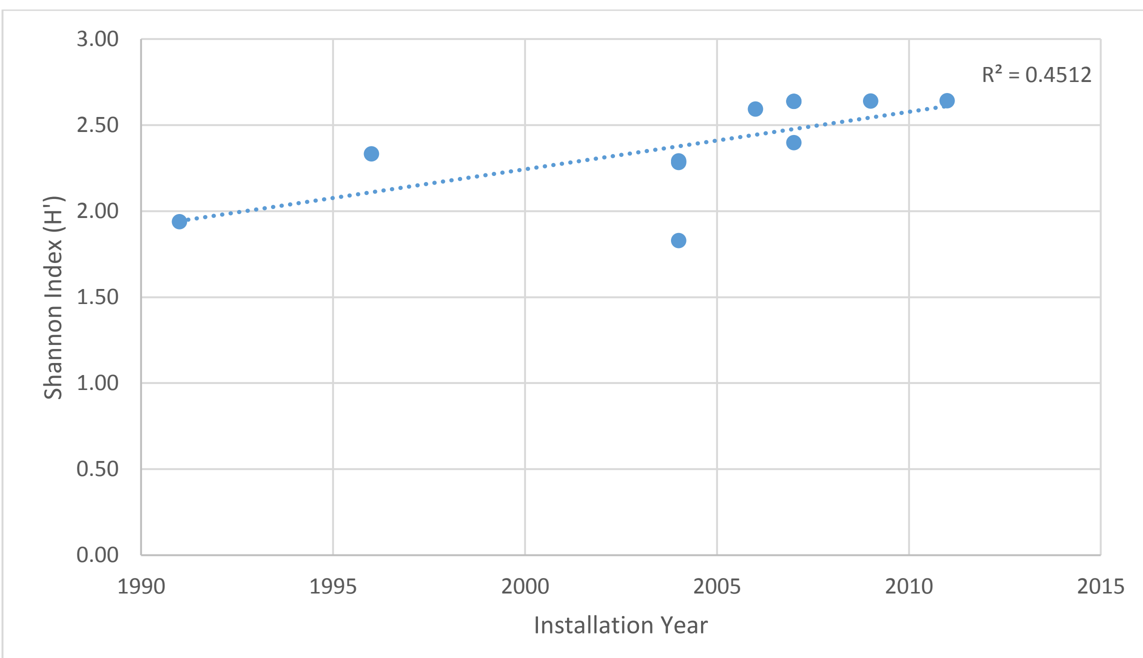
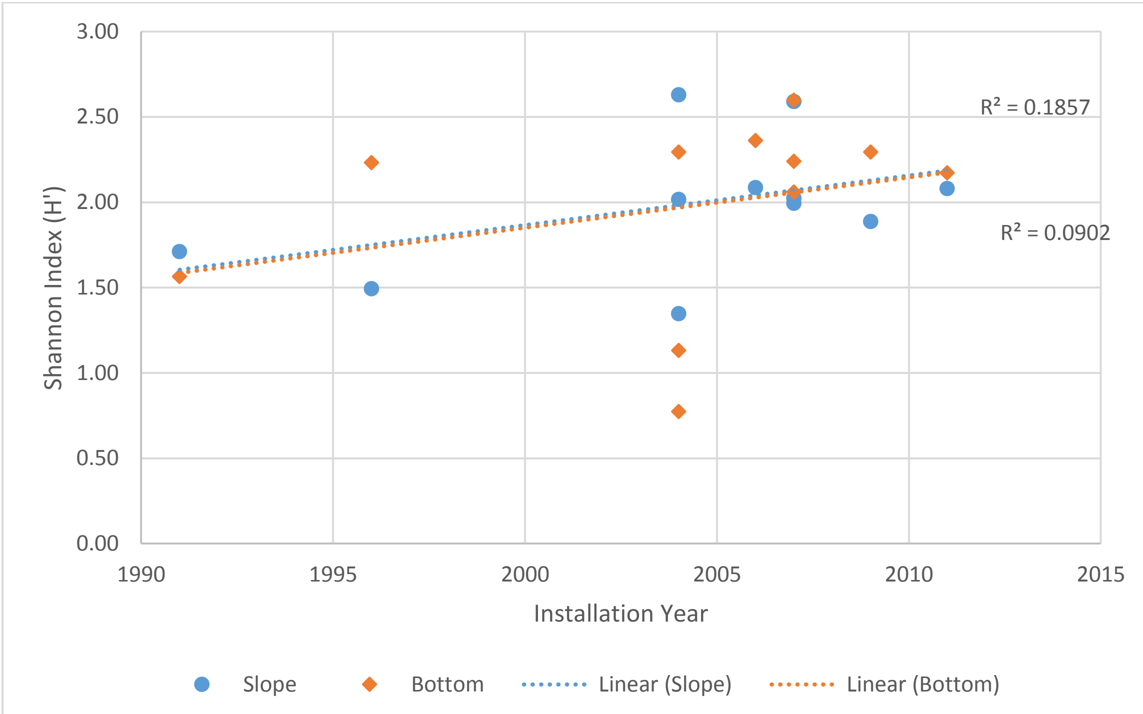


Figure 13: Shannon Diversity Index for slope and bottom samples as a function of basin installation year.

Note: Lines of best fit for slope and bottom data points effectively overlap.



Appendix F summarizes the results of the visual inspections of the eleven basins. Accumulation of litter or debris was the most prevalent condition (11 out of 11 sites) followed by standing water (10 out of 11) and sediment or debris buildup in and around the inlet (9 out of 11). In regards to the presence of standing water, some of the basins may have been designed to have a small permanent pool in order to provide additional water quality treatment.

DISCUSSION

Species Composition, Richness, Diversity and Basin Age

One of the goals of this study was to determine the relationship between basin age and species composition and dominance. Results do show a general negative correlation between H' and S and site age. Site H04 contains two basins in series (water from H04A flows into H04B) which were built at the same time however H04B's H' is larger than H04A's and the basins have different dominant species. These differences suggest another factor, such as basin configuration, play a more important role in determining species composition rather than age. Additionally, the large gap between the aggregate species count for the entire study, 119 species, and the largest number of species identified at a single site, 26 at H01, suggests a high degree of variability in the species composition at each site. The initial planting, proximity to other seed sources, and topography of the basin probably play an important role in the composition of the basin plant community in addition to time.

Detention basins and other stormwater management systems are challenging environments for plants to grow in because of pollutant loadings that can include excessive sediment, metals, and petroleum products along with a highly variable hydrology with periods of extreme inundation and dryness. These conditions could explain the general decreasing trend of richness and diversity with age. Over time characteristics of the basin may favor some species over others. However the imbalance of study site age prohibits the conclusion that age is the primary factor controlling the low richness and diversity at NO02. Additionally, lack of "rare" plant species may be attributed to the higher pollutant loading of the system as well as a lack of recruitment sources since most of the basins were sited in suburban neighborhoods or along highways.

The total species count for the study (119) is similar to species counts made at groups of mitigation wetlands; Balcombe et al. (2005) found 129 species in West Virginia sites while Leck and Leck (2005) found 92 species along the Delaware River in New Jersey. Table 7 lists Shannon Index values for plant communities in studies of constructed wetlands (usually for mitigation purposes) and reference wetlands. Constructed (also called created) wetlands serve as a reasonable environment for comparison to naturalized detention basins since both exist because of human intervention and share many common plants species by virtue of their similar hydrologic regimes. Thompson et al. (2007) included a stormwater “detention/retention” pond that had developed wetland vegetation in their study comparing plant diversity in created and restored wetlands. It is important to note that differences in sampling methodology could account for differences between H’ from study to study. Overall, the sites in Table 5 have lower H’ values than the sites in this study; this lends some support to the idea that detention basin characteristics promote diverse and perhaps novel plant communities.

Table 5: Shannon Index (H’) values for constructed wetland and related studies.

System Type	H’ Range or mean (std. err)	Location	Study
Constructed Wetland	0.59 – 1.68	Virginia, USA	Moser et al. 2007
Natural Wetland	0.65 – 1.11	Virginia, USA	Moser et al. 2007
Constructed Wetland	0.4 – 0.5	Virginia, USA	Dee and Ahn 2012
Wetland with restored hydrology (saturated zone)	0.5 (0.2)	Indiana, USA	Kellogg and Bridgham 2002
Wetland with restored hydrology (flooded zone)	0.2 (0.1)	Indiana, USA	Kellogg and Bridgham 2002
Wetland with restored hydrology and plants (saturated zone)	0.5 (0.1)	Indiana, USA	Kellogg and Bridgham 2002
Wetland with restored hydrology and plants (flooded zone)	0.3 (0.3)	Indiana, USA	Kellogg and Bridgham 2002
Natural Wetland (saturated zone)	0.8 (0.1)	Indiana, USA	Kellogg and Bridgham 2002
Natural Wetland (flooded zone)	1.0 (0.1)	Indiana, USA	Kellogg and Bridgham 2002
Restored Wetland	0.9 – 0.98	Ohio, USA	Thompson et al. 2007
Created Wetland	0.98 – 1.89	Ohio, USA	Thompson et al. 2007
Unplanned Wetland (detetion/retention pond)	1.19 (0.12)	Ohio, USA	Thompson et al. 2007

One reason biodiversity is highly valued in ecosystems is that biodiversity can create a resilient system that is able to survive in the face of disturbance (Haila and Kouki 1994). By this logic a diverse plant population is desirable in a detention basin because plant cover is necessary to maintain the integrity of the basin soil.

The dominant species identified in the study are a mix of wetland and common weedy upland species. It is reasonable to assume the given their reputation as weedy or undesirable species, *A. vulgaris, P. australis, C. varia, and L. salicaria,* were probably not planted but rather colonized the basin. When considering the twelve most abundant species, the conditions in the basin do not seem to favor indigenous or nonindigenous species. Despite being a somewhat “disturbed” environment, only 4 of the 12 most abundant species are classed as invasive. Frequent inundation of the floor of the basin explains the prevalence of obligate, facultative wetland, and facultative species in the basin bottom samples as compared to the drier, sloped sides. At some sites mowing may also influence which species have become established around the perimeter of the basin; there was no evidence of mowing any of the basin bottoms. Given the long list of species that could potentially grow in detention basins, it may be worthwhile to plant a large variety of species with the understanding that over time the unique features of the site will select out the best species for the basin.

Classifying the study sites as wetlands is outside the scope of this study, however it is relevant to note that 6 of the basins host plant communities that qualify as wetland communities according to USACE rules. The presence of hydrophytic plants is significant since a study of similar systems by Hogan and Walbridge (2007) showed how the plants and associated soil communities in naturalized basins could perform similar pollutant removal functions as natural wetlands.

Basin Performance

The results of the basin assessment (Appendix F) suggest the study basins may actually be too good at removing sediment since 9 of the 11 basins had a buildup of sediment and debris in at least one inlet pipe. This 82% rate is quite large compared to the 40% occurrence rate in the Hamilton Township Assessment which contained predominantly turfed basins, though the Hamilton study had a larger sample size. The clogged inlets found in the naturalized basin study tended to have plants growing in the rock or gravel aprons at the inlet mouth; regularly removing vegetation in this part of the basin could help alleviate the clogging problem. During the assessment survey, 6 of the 11 basins had exposed soil. Exposed soil can compromise water quality performance by causing the basin to export sediment instead of retaining it. However with the exception of H01 and H22, the exposed soil patches were usually in the middle of the basin and appeared to be associated with areas where water ponds. H01 was the only site where the bare soil showed signs of scour.

Loss of volume because of sediment buildup is a concern in all detention basins, and the buildup of organic matter could also limit the hydraulic capacity of naturalized basins as well (Livingston et al. 1997). H01 was the only study site with sediment built up higher than its lower orifice (see Figure 13). The concrete low flow channels of H21 were mostly filled with sediment, though plant growth did not appear to be the cause of the buildup (Figure 14). Plant growth did appear to be impeding flow out of H04B since water was ponding at the inlet of the basin but no water was flowing out; a stand of *P. australis* appeared to be blocking the flowpath (Figure 15). The potential volume loss from organic matter accumulation could be determined by surveying the basin to measure its volume. Volume loss could be partially offset by the soil's permeability in addition to plant evapotranspiration. Ideally such a study would be paired with measurements of the basin's soil properties since organic matter content can enhance the ability of a soil to store water (Hillel 2004).

Figure 14: Buildup of sediment around the outlet of H01.

Figure 15: Sedimentation of low flow channels in H21.

Figure 16: Plant growth in H04B appears to be obstructing flow.

Volume loss primarily impacts the ability of a detention basin to manage large events such as the 100 year storm which can completely fill a properly designed basin; volume loss is much less relevant to smaller storms that occur more frequently. It is important to note that these smaller storms also contribute more to the pollutant loading of the system (Kropp 1982, Griffin 1980) and that one advantage of naturalizing a basin is enhanced pollutant removal (which is described in greater detail in the following section). The issue of volume loss from plant growth presents a tradeoff question: should the basin be better at improving the water quality of frequent, small storms, or managing large volume, infrequent storms? The answer to the question is highly dependent on both site needs and regulatory priorities.

Ecosystem Functions

Del Tredici (2010) suggests that urban environments – those significantly altered by human activity – should not be overlooked for their biological value. He argues that plant communities that colonize disturbed environments should be valued and managed for the ecological services they provide. Naturalized detention basins fit into the category of urban environments – they are constructed by humans, often replace a different type of ecosystem (e.g. forest or agricultural land), and are consistently subjected to anthropogenic inputs in the form of nonpoint source pollution. From this perspective, it is worth considering naturalized basins for more than their primary function of managing stormwater peak flow.

Traditionally, turf has been used as groundcover in detention basins to stabilize soil and prevent erosion which would otherwise compromise the integrity of the basin (Livingston et al. 1997). While a monoculture of grass accomplishes this purpose, utilizing a variety of other plants can enhance the ecosystem services these systems could provide. Out of the 17 ecosystem services described by Costanza et al. (1997), the vegetation of naturalized basins have the ability to provide the following: ***gas regulation (e.g. carbon sequestration), water regulation, erosion and sediment control, waste treatment, nutrient cycling, pollination,*** and ***refugia*** (habitat for other populations).

Given the prevalence of wetland species and the wetland-like hydrologic conditions in the study sites, it is worth considering the role of naturalized basins in ***gas regulation*** of atmospheric carbon. Wetlands play a complex role in the global carbon cycle as major sources of greenhouse gases (i.e. carbon dioxide, methane, and nitrous oxide) but are also able to store carbon in plant material and organic soils. In their review, Kayranli et al. (2009) emphasize the importance of soil type, climate, and hydrologic regime as factors which influence whether or not a freshwater wetland serves as a source or sink for carbon. They report that carbon dioxide emissions are higher under drained conditions since decomposition occurs more rapidly in an aerobic soil environment. Given the frequent wetting and drying of detention basins, they may be less than ideal for carbon sequestration. However further research would be needed to quantify carbon fluxes into and out of these systems.

The vegetation community in stormwater detention basins have the potential to provide ***regulation of the water cycle*** as an ecosystem service in the basin through evapotranspiration (ET). New stormwater practices and low impact development emphasize stormwater volume reduction techniques in order to mimic the hydrology of undeveloped land. Water loss through ET may be a viable source volume reduction in naturalized detention basins. Given the prevalence of wetland species found in the study's basins, it is worth considering the basins as wetland type systems to estimate the role of ET in the water budget of the basin. ET is a function of meteorology (e.g. relative humidity, solar radiation, wind speed), land surface, and plant type. Wetlands pose a particular challenge for measuring and modeling ET because their highly variable surface cover includes varying ratios of bare soil, water and vegetation - which in and of itself can be highly diverse (Drexler et al. 2004).

Studies of entire marsh systems report mean daily ET rates ranging from 0.16 to 0.18 inches per day (See Table 8 for further details). Using basin PI05 as an example, this sort of marsh vegetation could remove up to 23% of the influent stormwater volume generated by the New Jersey water quality storm. As the storms increase in size, the volume reduction rate drops; the ET of a marsh could only handle about 2.3% of the 100 year storm volume. Treating smaller storms is valuable since they occur with the greatest frequency (Charles et al. 1993).

Pauliukonis (2001) suggests wetlands may be ET hotspots in a landscape as many wetland plants have higher ET rates than upland species since wetland plants are not usually limited by water supply. Yet a review of ET rates for *Poa pratensis* (Kentucky bluegrass), a typical species used in lawns and detention basins, ranges from 0.15 to 0.48 in. per day (also shown in Table 6). Reported ET rates for other cool season grass speceies range from 0.28 to 0.33 in./day. The comparatively higher ET rates of turf species could translate to volume reductions of 41% with a water storm at PI05 (assuming mean turf ET of 0.39 in./day).

Table 6: Evapotranspiration rates for select wetlands and plant species.

Species or environment	Mean ET rate or range	Source
Typha latifolia	0.23 in./day	Pauliukonis (2001)
Typha & Scirpus Marsh	0.16 in./day	Goulden et al. 2007
Bulrush Marsh	0.18 in./day	Stannard et al. 2013
Mixed Marsh	0.17 in./day	Stannard et al. 2013
Poa pratensis	0.15 to 0.48 in./day	Romero and Dukes 2009

Again when considering conventional design, detention basins provide a moderate amount of ***erosion and sediment control*** (Blick et al. 2004). At a bare minimum, plants are necessary in detention basins in order to prevent soil erosion within the basin (Livingston et al. 1997). Conditions that are too dry or too wet can inhibit turfgrass growth (Livingston et al. 1997) which is another reason planting more robust wetland plant species may be beneficial. Only one basin in the study showed signs of soil erosion and in this case the eroded area represented a very minor portion of the entire basin. The addition of microtopography and unmowed vegetation can enhance sediment removal by slowing the flow of water into and out of the basin, promoting sedimentation (Hogan and Walbridge 2007).

The comparatively short detention time and lack of anaerobic conditions in conventional detention basins limit their ability to treat pollutants in stormwater (***waste treatment***) (Livingston et al. 1997). Some wetland plants do have the ability to remove trace elements from storm and wastewater (Qian et al. 1999, Weiss et al. 2006); their addition to detention basin could enhance pollutant removal. Qian et al. (1999) recommended *Persicaria hydropiperoides* (a species found in 5 study basins) for wastewater treatment for its ability to sequester trace elements and its high productivity. These experiments mimicked a pond or wetland environment; dry detention basins typically have shorter periods of inundation which may decrease the effectiveness of their plants to remove trace pollutants. If vegetation detention basins are providing phytoremediation services, it may be necessary to periodically remove and treat vegetation that is sequestering toxic trace elements.

Nutrient cycling and ***waste treatment*** are closely linked in stormwater studies since high concentrations of nitrogen and phosphorus are common in stormwater (USEPA 1983). In an experiment with constructed wetlands, systems with emergent vegetation had the highest nitrogen removal rates (Weisner and Thiere 2010). The authors posit that the high productivity of emergent vegetation produces adequate organic matter to support the bacterial communities that facilitate denitrification. Species richness was positively correlated with the retention of NO_3-N and NH_4-N in a vertical flow wastewater treatment wetland; this could be attributed higher root density associated with higher richness or with increased activity with associated microbial communities (Zhu et al. 2010). Naturalized basin soils also exhibit similar phosphorus sorption capacities when compared to their conventional basin counterparts (Hogan and Walbridge 2007).

While detention basins are not appropriate for the production of food or other commercially valuable plants, their unmowed vegetation can provide food for pollinator species, thus indirectly supporting ***pollination*** ecosystem services. Thirty-nine of the 119 plant species identified in the study can provide nectar and pollen to honeybees (UGA 2011, Tew 1998, and NJBA 2013). Jha and Kremen (2013) found a positive correlation between floral diversity and bumble bee nesting density in California, though increasing road density had the opposite effect. The higher plant community diversity of bioretention basins in suburban Australian neighborhoods were also able to support higher richness of insect species compared to adjacent plots of turf (Kazemi et al. 2009). These studies suggest that the diverse plant communities found at the study sites can support diverse insect communities that provide important ecosystem services.

Informal observations made during plant surveys and other research suggest that detention basins can serve as ***refugia*** or habitat for several animal species. Table 7 lists four bird species observed at the highway study sites; all are generally associated with aquatic and wetland habitats. With the exception of the killdeer, the other three bird species were also identified at stormwater ponds in Guelph, Canada (Bishop et al. 2000A). Other wildlife surveys have found frog, toad, fish, reptiles, and other bird species using stormwater ponds (Bishop et al. 2000A, McCarthy and Lathrop 2011, Brand and Snodgrass 2010). While stormwater basins and ponds can provide additional habitat for species in an urbanized landscape, there is an associated risk for these animals given the ability of these systems to store pollutants. All 15 ponds in the Bishop et al. (2000B) study contained contaminants including polychlorinated biphenyls (PCBs), metals, and polyaromatic hydrocarbons (PAHs) at concentrations which exceeded Lowest Effects Levels for Canadian Water Quality Standards. Sparling et al. (2004) measured elevated levels of zinc and copper in 8 day old red-wing blackbirds and suggested that nestlings may have been stressed and impaired by elevated zinc levels in the environment, though the study could not rule out other possible sources of stress on the nestlings. While there are potential toxicity risks associated with the pollutants in detention basins, it is not feasible to prevent wildlife from using these basins. It is more reasonable to provide wildlife with higher quality habitat in urban and suburban landscapes and to utilize naturalized basins as supplementary, not replacement, habitat.

Table 7: Animal species observed during site visits.

Species	Common Name	Site
Branta Canadensis	Canada Goose	H22,
Agelaius phoeniceus	Red-Winged Blackbird	H03, H08, H17
Charadrius vociferous	Killdeer	H21, H22
Anas platyrhynchos	Mallard Duck	H04A

CONCLUSION

The eleven basins investigated in this study demonstrate that naturalized basins are capable of hosting diverse plant communities for at least two decades after their creation. Microtopography seems to favor the growth of both upland and wetland plant species, contributing to the diversity of the basins. Further study is needed, particularly of older naturalized basins, to clarify the relationship between species richness and diversity and system age. Plant growth in the basins can contribute to the clogging on inlets, though periodic removal of vegetation from the inlet openings may address this issue. Naturalized basins have the ability to contribute ecosystem services to the urban landscape, particularly through water regulation, erosion and sediment control, waste treatment, nutrient cycling, pollination and refugia. Future research should focus on quantifying the services of these systems.

Chapter 6 – Conclusion and Future Research Needs

Through observing soil properties, basin conditions, and plant communities and modeling hydrologic performance, this study suggests that overall, detention basins are robust systems that can continue to perform their intended function over the course of 30 years. Granted, characteristics of a particular site such as its influent pollutant loading and owner maintenance practices strongly influence the buildup of sediment and debris which can impair a basin's ability to function. The problem is that the performance of these basins is not adequate to meet current stormwater management standards. Planting wetland type vegetation holds promise as a retrofit option to improve pollutant removal since basins in the study were able to support plant growth for over 20 years.

The study investigated soil infiltration rates with the premise that sedimentation over time would cause clogging so older basins would have lower saturated hydraulic conductivity rates (K_{sat}). Measurements made at 10 sites did not disprove the hypothesis that basin age would alter the saturated hydraulic conductivity (K_{sat}) of soils in the bottom of detention basins. Though soil types underlying each basin had similar characteristics, basin soil may have been a confounding factor in the study along with basin design. However when comparing the reported limiting K_{sat} values to measured K_{sat}, the oldest study sites built in the 1980s were only ones with measured K_{sat} consistently lower than reported. This could suggest some degree of soil clogging, though more research on the soil properties of older detention basins is needed. Since detention basins have moderate TSS removal rates, clogging and reduction of infiltration may be less of a problem in these systems which means they have the potential to provide a moderate amount of groundwater recharge, though probably not enough to fulfill regulatory requirements.

In general, the five sites used in the design study continue to meet the 1983 New Jersey performance standards they were designed to fulfill, though 3 of the sites no longer treat smaller storms as well as they should. The results for the 2004 standards are more mixed. For peak flow reduction, none of the sites could treat the 2-year storm to 2004 standards, one could treat the 10-year storm, and three could meet the 100-year storm. Additionally none of the sites could provide 80% TSS removal or infiltrate a 2 year storm as per the new rules. At best, one site has the potential to infiltrate 36% of the target groundwater recharge volume. The design analysis project demonstrates that while the detention basins do continue to function, from a regulatory perspective they have become obsolete and only partially meet our needs to for environmental protection.

The structure and condition project initially hypothesized that a detention basin's concrete structures deteriorate with age and that older basins would be in worse condition than newer ones. However the results of the study do not show any strong time based trends and consequently do not support this hypothesis. A major drawback with the dataset is an uneven distribution of samples in each age group. Though large variation in the conditions of detention basins in a younger cohort suggests other factors such as maintenance, influent characteristics, and the quality of the installed structure may be more important in influencing site condition. Debris and sediment accumulation were the most prevalent conditions in the Hamilton Township dataset and a chi-square analysis showed a significant association between material accumulation in inlets, the basin bottom, and the outlet. There is also a significant association between the presence of debris accumulation at the outlet and standing water in the basin which emphasizes the importance of keeping the outlet opening clear in order to prevent unwanted ponding. It appears that with good quality structural components and regular cleaning maintenance, a basin can remain in decent functioning condition for at least 30 years.

The analysis of 11 naturalized detention basins demonstrates that these sites are able to sustain diverse plant communities for upwards of 20 years. Data did show a weak decreasing trend of both Shannon Diversity Index and species richness with age. This trend may either be a reflection of differences in initial plantings or of species selection by basin characteristics as the system ages. In addition to improving pollutant removal, plant growth can be a source of other ecosystem services, including water regulation, erosion control, waste treatment, nutrient cycling, pollination, and refugia. Further quantification of ecosystem services by detention basins could be an interesting avenue of research, particularly in the context of the wider interest in documenting ecosystem services in the United States. The most common problem identified with plant growth in the basins were inlet clogging from plant growth in the inlet's gravel apron. Regular clearing of the gravel apron, or perhaps the installation of a larger concrete apron, may prevent this problem.

FUTURE RESEARCH NEEDS

All of the projects conducted for this thesis would be improved by including additional older detention basins to the sample pool in order to produce more even age distribution. The projects could also be repeated in other parts of New Jersey or the county in order to determine if the results are regionally specific or reflect broader trends

Soils

The Piedmont soils under the study sites were fairly slow draining. Infiltration measurements could be made a basins with very different soil types to compare groundwater recharge performance. Basins in New Jersey's Coastal Plain and Highlands region would be good candidates for this study. Instead of relying on computer modeling, groundwater recharge in a detention basin could also be determined by creating a water budget for a basin. Measuring the difference between water volume flowing into or out of a detention basin should provide reasonable estimates for volume loss to groundwater recharge and evapotranspiration. Comparing the recharge rates between turf and naturalized basins would be valuable for discussion about the benefits of one type of basin over another. The previously described water budget technique could be useful for this purpose.

Design

Future modeling efforts of existing detention basins could test the effects of retrofitting outlets and adding other stormwater control measures, such as rain barrels, to properties. Models could be used to determine the optimal retrofits for a property or set of properties. It would be interesting to see if one particular type of retrofit would be generically effective or if retrofits would need to be tailored on a site by site basis. The National Research Council (2008) recommends an increase in the amount of functionality monitoring for detention basins and other stormwater control measures. One type of functionality monitoring includes measuring water depth in a basin during or after a rainstorm. Future research on basin design could examine the feasibility of such a monitoring method. Though the unique designs of each basin and variability in rainfall depths would pose significant logistical challenges.

Structure

The study data suggests other factors are influencing the condition of basin structural components in addition to time. Future research should investigate other potential causes of structural deterioration. The Hamilton Township dataset could be expanded to include additional information about the basins such as adjacent land use or system configuration to identify potential factors that result in poor basin conditions.

Vegetation

Further quantifying the ecosystem services provided by both turf and naturalized detention basins is necessary in light of growing interest in the idea of measuring and tracking ecosystem capital. Future research projects could work to identify other basin characteristics that may influence community composition in order to provide more guidance on basin planting choice and design. Detention basins can become naturalized through intentional landscaping plan or through neglect and volunteer colonization of plants. Documenting the differences between these two types of systems may reveal the necessity of treating them as one or two classes of systems.

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Appendix A – Typical Soil Profiles for Native Soils at Infiltration Study Basins (NRCS 2012)

LbtB—Lansdowne silt loam, 2 to 6 percent slopes

0 to 7 inches: Silt loam

7 to 13 inches: Silt loam

13 to 45 inches: Silty clay

45 to 60 inches: Stratified sandy loam to channery silty clay

60 to 157 inches: Weathered bedrock

KkoB—Klinesville channery loam, 2 to 6 percent slopes

0 to 8 inches: Channery loam

8 to 12 inches: Channery silt loam

12 to 157 inches: Weathered bedrock

NknB—Nixon loam, 2 to 5 percent slopes

0 to 8 inches: Loam

8 to 11 inches: Loam

11 to 30 inches: Loam

30 to 40 inches: Sandy loam

40 to 60 inches: Stratified loamy sand to gravelly sandy loam to sandy clay loam

NkpB—Nixon-Urban land complex, 0 to 5 percent slopes

0 to 8 inches: Loam

8 to 11 inches: Loam

11 to 30 inches: Loam

30 to 40 inches: Sandy loam

40 to 60 inches: Stratified loamy sand to gravelly sandy loam to sandy clay loam

RehA—Reaville silt loam, 0 to 2 percent slopes

0 to 10 inches: Silt loam

10 to 15 inches: Channery silt loam

15 to 22 inches: Channery silt loam

22 to 28 inches: Very channery silt loam

28 to 157 inches: Weathered bedrock

PbpA—Parsippany silt loam, 0 to 3 percent slopes

0 to 2 inches: Silt loam

2 to 8 inches: Silt loam

8 to 46 inches: Silty clay

46 to 60 inches: Sandy loam

EkaAr—Elkton loam, 0 to 2 percent slopes, rarely flooded

0 to 8 inches: Loam

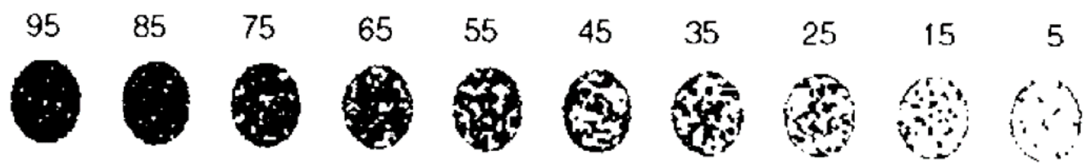
8 to 35 inches: Clay loam

35 to 60 inches: Clay loam

Appendix B – Middlesex County Conditions Assessment Form

Condition Assessment Form

Date:
Site Name:
Location:
Notes:



1) What percent of the inlet(s) is damaged with cracking, spalling, rusting?

Percent Damage	0%	1-25%	26-50%	51-75%	76-100%	Final Score
Score	1	2	3	4	5	
Inlet 1						
Inlet 2						
Inlet 3						
Inlet 4						
Inlet 5						
					Mean Score	

2) What percent of the outlet is damaged with cracking, spalling, rusting?

Percent Damage	0%	1-25%	26-50%	51-75%	76-100%	Final Score
Score	1	2	3	4	5	
Outlet						

Is there debris, litter, and/or sediment accumulated in or around the any of the:

	Yes	No
Score	1	0
3) Inlets?		
4) Low flow channels?		
5) Outlet?		

Does the basin have:

	Yes	No
Score	1	0
6) Trash racks on outlet?		
7) Low flow channels?		

Appendix C – Rutgers Water Resources Program Hamilton Township Detention Basin Conditions Assessment Form

RUTGERS
New Jersey Agricultural Experiment Station
Water Resources Program

Hamilton Township Stormwater Infrastructure Assessment Program
Stormwater Basin Inspection Checklist

Hamilton
A Destination
"America's Favorite Hometown"

GENERAL INFORMATION		Site ID:
Name(s) person inspecting the basin:		Date:
Location Address and Cross Streets:	Watershed:	
Name of Creek, Stream, or area into which the basin discharges:	Property Owner / Tax Parcel Block & Lot:	
Contact information:		
STRUCTURAL COMPONENTS		
Basin description, size and depth:	Is the basin accessible to maintain? Yes / No Is it maintained: Mowed, clear of woody plants, inlet/outlet blockages?	
Number of inlets:	Outlet diameter:	

GENERAL OBSERVATIONS	YES	NO	NOTES/REMARKS
1) Any reports on the basin not functioning?			
2) Are there any unauthorized or malfunctioning structures in the basin?			
3) Are there concrete low flow channels. Is the water entering the basin directly exiting the basin outlet without coming in contact with the basin bottom soil and vegetation?			
4) Is there standing water or evidence of standing water in the basin?			
INLET/S			
1) Signs of breakage, damage, corrosion or rusting of inlet structure/pipe?			
2) Debris or sediment accumulation in or around the inlet clogging the inlet opening/pipe?			
3) Signs of erosion, scour or gullies; rock or vegetation above or around the inlet structure?			
4) Tree roots, woody vegetation growing close to or through the inlet structure or a situation impacting the structure's integrity?			
5) If the inlet has a pretreatment structure (trash rack, forebay) is it filled w/ debris or sediment?			
BASIN			
1) Accumulation of debris or litter within basin?			
2) Exposed dirt or earth visible, are there areas without vegetation or where turf is damaged?			
3) Excess sediment accumulation in the basin?			
4) Basin walls/embankment eroded, slumping, caved or being undermined?			

RUTGERS
New Jersey Agricultural Experiment Station

Hamilton Township Stormwater Infrastructure Assessment Program
Stormwater Basin Inspection Checklist

OUTLET	YES	NO	NOTES/REMARKS
1) Breakage, damage, corrosion or rusting to outlet pipe or conveyance?			
2) Signs of erosion, scour or gullies; rock or vegetation above or around the outlet structure?			
3) Debris or sediment accumulation in or around the outlet pipe (i.e. debris or sediment)?			
4) Accumulation of debris or litter in or around outlet?			
5) Tree roots or woody vegetation impacting the outlet or causing potential damage to the structure?			
SECONDARY/EMERGENCY OVERFLOW SPILLWAY			
1) Are pipes, conduits, or conveyances free of debris, clogs and in good condition? (i.e. no visible cracks, breakage slumping)			
2) Large tree or root growth close to pipes or conveyances with the potential to crack structure or impede flow?			
3) Signs of erosion, scour or gullies; rock or vegetation above or around the spillway?			
BASIN OUTFALL AREA			
1) Signs of stormwater exiting the basin in an uncontrolled manner over or through wall or berm?			
2) Signs of erosion, scour or gullies; rock or vegetation at or down slope of the outfall?			

RECOMMENDATIONS FOR WATER QUALITY IMPROVEMENTS	
1) Reduce mowing 2) Plant buffers 3) Establish meadows 4) Retrofit with infiltration structures or other strategies 5) Other	

SUMMARY AND NOTES: Identify unique characteristics and/or opportunities

Appendix D: Naturalized Detention Basin Study Full Species List

Genus	Species	Family	Common Name
Agrostis	stolonifera	Poaceae	creeping bentgrass
Ailanthus	altissima	Simaroubaceae	tree of heaven
Alisma	subcordatum	Alismataceae	water plantain
Allium	vineale	Liliaceae	wild garlic
Ambrosia	artemesiifolia	Asteraceae	annual ragweed
Apocynum	cannabinum	Apocynaceae	indianhemp
Artemisia	vulgaris	Asteraceae	mugwort
Asclepias	syriaca	Asclepiadaceae	common milkweed
Barbarea	vulgaris	Brassicaceae	yellow rocket
Betula	nigra	Betulaceae	river birch
Bidens	polylepsis	Asteraceae	bearded beggartick (or aristosa)
Bidens	vulgata	Asteraceae	devils beggartick
Bidens	frondosa	Asteraceae	devils beggartick
Bidens	connata	Asteraceae	purplestem beggartick
Calla	palustris	Araceae	water arum/wild calla
Calystegia	silvatica	Convolvulaceae	morning glory
Capsella	bursa-pastoris	Brassicaceae	shepherd's purse
Carex	vulpinoidea	Cyperaceae	fox sedge
Carex	projecta	Cyperaceae	necklace sedge
Carex	lurida	Cyperaceae	shallow sedge
Centaurea	maculosa	Asteraceae	spotted knapweed
Centaurea	nigrescens	Asteraceae	tyrol knapweed
Chenopodium	album	Chenopodiaceae	common lambsquarters
Cichorium	intybus	Asteraceae	chicory
Cirsium	vulgare	Asteraceae	bull thistle
Cirsium	arvense	Asteraceae	canada thistle
Conyza	canadensis	Asteraceae	horseweed
Cornus	sericea	Cornaceae	redoiser dogwood
Coronilla	varia	Fabaceae	crown vetch
Cuscuta	americana	Cuscutaceae	dodder
Cyperus	esculentus	Cyperaceae	yellow nutsedge
Daucus	carota	Apiaceae	Queen Anne's lace
Digitaria	sanguinalis	Poaceae	hairy crabgrass
Echinochloa	crusgalli	Poaceae	barnyard grass
Eclipta	prostrata	Asteraceae	false daisy
Eleocharis	obtusa	Cyperaceae	spike rush
Erigerson	strigosus	Asteraceae	daisy fleabane

Genus	Species	Family	Common Name
Eupatorium	serotinum	Asteraceae	lateflowering thoroughwort
Euphorbia	esula	Euphorbiaceae	leafy spurge
Euthamia	graminifolia	Asteraceae	flat-top goldentop
Glechoma	hederaceae	Lamiaceae	ground ivy
Gleditsia	triacanthos	Fabaceae	honeylocust
Heteranthera	reniformis	Pontederiaceae	kidneyleaf mudplantain
Impatiens	capensis	Balsaminaceae	jewelweed
Juncus	effusus	Juncaeae	common rush
Juncus	tenuis	Juncaeae	path rush
Juncus	bufonius	Juncaceae	toad rush
Juniperus	virginiana	Cupressaceae	eastern redcedar
Kochia	scoparia	Chenopodiaceae	kochia
Lactuca	serriola	Asteraceae	prickly lettuce
Lactuca	canadensis	Asteraceae	wild lettuce
Leersia	oryzoides	Poaceae	rice cutgrass
Lepidium	virginicum	Brassicaceae	Virginia pepperweed
Linaria	vulgaris	Scrophulariaceae	butter and eggs
Liquidambar	styraciflua	Hamamelidaceae	sweetgum
Lolium	perenne	Poaceae	perennial ryegrass
Lonicera	japonica	Caprifoliaceae	Japanese honeysuckle
Lotus	corniculatus	Fabaceae	bird's-foot trefoil
Ludwigia	palustris	Onagraceae	marsh purslane
Lythrum	salicaria	Lythraceae	purple loosestrife
Magnolia	virginiana	Magnoliaceae	sweetbay magnolia
Mikania	scandens	Asteraceae	climbing hempvine
Miscanthus	sinensis	Poaceae	
Oenothera	biennis	Onagraceae	evening primrose
Oxalis	stricta	Oxalidaceae	common wood-sorrel
Oxalis	corniculata	Oxalidaceae	creeping woodsorrel
Panicum	dichotomiflorum	Poaceae	fall panicum
Paspalum	laeve	Poaceae	field beadgrass
Persicaria	lapathifolia	Asteraceae	dock leaf smartweed
Persicaria	pensylvanica	Polygonaceae	smartweed
Persicaria	maculosa	Polygonaceae	spotted ladysthumb
Persicaria	hydropiperoides	Polygonaceae	swamp smartweed
Persicaria	maculosa	Polygonaceae	
Phalaris	arundinacea	Poaceae	reed canarygrass
Phragmites	australis	Poaceae	common reed
Pilea	pumlia	Urticaceae	canadian clearweed
Plantago	major	Plantaginaceae	broadleaf plantain
Plantago	lanceolata	Plantaginaceae	narrowleaf plantain

Genus	**Species**	**Family**	**Common Name**
Poa	pratensis	Poaceae	Kentucky bluegrass
Polygonum	sagittatum	Polygonaceae	arrowleaf tearthumb
Populus	tremuloides	Salicaceae	quaking aspen
Potentilla	simplex	Rosaceae	common cinquefoil
Pyrus	communis	Rosaceae	common pear
Quercus	spp.	Fagaceae	red oak species
Rhus	typhina	Anacardiaceae	staghorn sumac
Robinia	pseudoacacia	Fabaceae	black locust
Rosa	multiflora	Rosaceae	multiflora rose
Rumex	crispus	Polygonaceae	curly dock
Salix	discolor	Salicaceae	pussy willow
Schoenoplectus	tabernaemontani	Cyperaceae	softstem bulrush
Schoenoplectus	pungens	Cyperaceae	threesquare
Scirpus	georgianus	Cyperaceae	Georgia bulrush
Scirpus	cyperinus	Cyperaceae	woolgrass
Setaria	viridis	Poaceae	green foxtail
Setaria	lutescens	Poaceae	yellow foxtail
Solanum	dulcamara	Solanaceae	climbing nightshade
Solanum	physalifolium	Solanaceae	hoe nightshade
Solidago	canadensis	Asteraceae	Canada goldenrod
Strophostyles	helvola	Fabaceae	wild bean
Symphyotrichum	oblongifolium	Asteraceae	aromatic aster
Symphyotrichum	dumosum	Asteraceae	bushy aster (= Forbe F)
Symphyotrichum	pilosum	Asteraceae	
Taraxacum	officinale	Asteraceae	common dandelion
Toxicodendron	radicans	Anacardiaceae	poison ivy
Tridens	flavus	Poaceae	purpletop
Trifolium	hybridum	Fabaceae	alsike clover
Trifolium	pratense	Fabaceae	red clover
Trifolium	repens	Fabaceae	white clover
Typha	latifolia	Typhaceae	broadleaf cattail
Typha	angustifolia	Typhaceae	narrowleaf cattail
Urtica	dioica	Urticaceae	stinging nettle
Vitis		Vitaceae	wild grape species
Xanthium	strumarium	Asteraceae	common cocklebur

Appendix E: Four most prevalent species by relative dominance (RD) at each detention basin

Species	RD	Wetland Indicator	Invasive?	Indigenous?
Site: H01				
Artemesia vulgaris	0.19	UPL	Noninvasive	Nonindigenous
Leersia oryzoides	0.18	OBL	Noninvasive	Indigenous
Echinochloa crusgalli	0.14	FAC	Noninvasive	Nonindigenous
Symphyotrichum oblongifolium	0.09	UPL	Noninvasive	Indigenous
Site: H02				
Bidens polylepsis	0.16	FACW	Noninvasive	Indigenous
Typha spp.	0.11	OBL	Invasive	Indigenous
Panicum dichotomiflorum	0.10	FACW	Noninvasive	Indigenous
Echinochloa crusgalli	0.10	FAC	Noninvasive	Nonindigenous
Site: H03				
Eleocharis obtusa	0.19	OBL	Noninvasive	Indigenous
Unknown poaceae	0.14	Unknown	Unknown	Unknown
Artemesia vulgaris	0.12	UPL	Noninvasive	Nonindigenous
Lythrum salicaria	0.09	OBL	Invasive	Nonindigenous
Site: H04A				
Typha spp.	0.46	OBL	Invasive	Indigenous
Phragmites australis	0.25	FACW	Invasive	Nonindigenous
Liquidambar styraciflua	0.06	FAC	Noninvasive	Indigenous
Potentilla simplex	0.05	FACU	Noninvasive	Indigenous
Site: H04B				
Coronilla varia	0.25	Unknown	Invasive	Nonindigenous
Unknown poaceae	0.25	Unknown	Unknown	Unknown
Phragmites australis	0.11	FACW	Invasive	Nonindigenous
Persicaria hydropieroides	0.09	OBL	Noninvasive	Indigenous
Site: H08				
Unknown poaceae	0.32	Unknown	Unknown	Unknown
Lotus corniculatus	0.14	FACU	Noninvasive	Nonindigenous
Plantago lanceolata	0.08	FACU	Noninvasive	Nonindigenous
Lythrum salicaria	0.08	OBL	Invasive	Nonindigenous
Site: H17				
Artemesia vulgaris	0.34	UPL	Noninvasive	Nonindigenous
Phragmites australis	0.09	FACW	Invasive	Nonindigenous
Schoenoplectus pungens	0.08	OBL	Noninvasive	Indigenous
Persicaria hydropieroides	0.06	OBL	Noninvasive	Indigenous
Site: H21				
Unknown poaceae	0.31	Unknown	Unknown	Unknown
Persicaria pennsylvanica	0.20	FACW	Noninvasive	Indigenous
Cyperus esculentus	0.12	FACW	Noninvasive	Indigenous
Phragmites australis	0.06	FACW	Invasive	Nonindigenous
Site: H22				

Species	RD	Wetland Indicator	Invasive?	Indigenous?
Agrostis stolonifera	0.22	FACW	Noninvasive	Nonindigenous
Trifolium repens	0.10	FACU	Noninvasive	Nonindigenous
Echinochloa crusgalli	0.08	FAC	Noninvasive	Nonindigenous
Tridens flavus	0.08	UPL	Noninvasive	Indigenous
Site: NE01				
Unknown poaceae	0.28	Unknown	Unknown	Unknown
Euthamia graminifolia	0.13	FAC	Noninvasive	Indigenous
Juncus effuses	0.12	OBL	Noninvasive	Indigenous
Leersia oryzoides	0.12	OBL	Noninvasive	Indigenous
Site: NO02				
Leersia oryzoides	0.30	OBL	Noninvasive	Indigenous
Persicaria hydropiperoides	0.21	OBL	Noninvasive	Indigenous
Impatiens capensis	0.20	FACW	Noninvasive	Indigenous
Symphyotrchum pilosum	0.07	FACU	Noninvasive	Indigenous

Appendix F: Summary of findings from inspection of naturalized detention

Based on Hamilton Township Stormwater Infrastructure Assessment Program Stormwater Basin Inspection Checklist. (X indicates presence of condition.)

Site (year)	NO02 (1991)	H04A (2004)	H22 (2011)	NE01 (1996)	H17 (2006)	H21 (2004)	H01 (2007)	H02 (2007)	H03 (2009)	H08 (2009)	H04B (2004)	Total Occurrences	Percent Occurrences
GENERAL OBSERVATIONS													
1) Any reports on the basin not functioning?												0	0%
2) Any unauthorized or malfunctioning structures in the basin?												0	0%
3) Are there concrete low flow channels?												0	0%
4) Is there standing water or evidence of standing water in the basin?		x	x	x	x	x	x	x	x	x	x	10	91%
INLETS													
1) Signs of breakage, damage, corrosion or rusting of inlet?					x	x						2	18%
2) Debris or sediment accumulation in or around inlet clogging the opening/pipe?		x	x	x	x		x	x	x	x	x	9	82%
3) Signs of erosion, scour or gullies around inlet structure?												0	0%
4) Tree roots, woody vegetation growing close to or through inlet structure?	x				x							2	18%
BASIN													
1) Accumulation of litter or debris in basin?	x	x	x	x	x	x	x	x	x	x	x	11	100%
2) Exposed dirt or earth visible, are there areas			x	x	x	x	x	x				6	55%

without vegetation or where turf is damaged?													
3) Excess sediment accumulation in basin?						x					x	2	18%
4) Basin walls/embankment eroded, slumping, cave or being undermined?												0	0%
(continued on next page)													
OUTLET													
1) Breakage, damage, corrosion or rusting to outlet pipe or conveyance?	x		x	x			x					4	36%
2) Signs of erosion, scour or gullies around outlet structure?							x					1	9%
3) Debris or sediment accumulation in or around outlet pipe?	x	x	x	x		x					x	6	55%
4) Accumulation of litter in or around outlet?	x	x	x	x	x	x	x	x		x		9	82%
5) Tree roots or woody vegetation impacting the outlet or causing potential damage?												0	0%