MONITORING AND MODELING IMPACTS OF A RAIN GARDEN ON THE UNIVERSITY OF GEORGIA CAMPUS

by

LAURA KEYS

(Under the Direction of Laurie Fowler)

ABSTRACT

I collected samples and hydrologic data from the inflow and outflow of a campus rain garden for 10 storm events over eight months. The rain garden consistently decreased loads of sediment, ammonium, and total phosphorus and consistently increased loads of nitrate. I also modeled the collective impacts of rain gardens in two Athens-area watersheds for a 10-year period using SWAT. The urban watershed experienced frequent large peak discharges in storm events, while the forested watershed showed less frequent, lower peak discharges from those same storms. Routing 30% of runoff generated by an urban watershed through rain gardens showed reductions in peak discharge of 30% and did not "overtreat" discharge or reduce peak discharge below that of a forested pre-development watershed. Numerous barriers exist that prevent the widespread installation of rain gardens across Georgia, and I discuss the role of policy in removing those barriers.

INDEX WORDS: stormwater, urban stream, rain garden, green infrastructure, LID, hydrology, pre-development, nutrients, watershed, modeling, policy

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LAURA KEYS

BS, Washington University in St. Louis, 2008

MS, University of California, Berkeley, 2010

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LAURA KEYS

Major Professor:	Laurie Fowler
Committee:	David E. Radcliffe
	Seth J. Wenger

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
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CHAPTER 1

INTRODUCTION AND RELATED WORK

Stormwater is one of the leading causes of stream impairments in the United States (USEPA 2014a). It is created when precipitation hits an impervious surface and rapidly makes its way downhill to eventually end up in surface water. Paved surfaces such as roads and parking lots prevent runoff from infiltrating into the ground; as a result, runoff enters streams in “flashy” high-volume, high-velocity floods that increase erosion and scouring (Burian & Pomeroy 2010). This altered hydrology leads to the so-called “urban stream syndrome” (Walsh et al. 2005), which includes elevated levels of sediments, chemicals, and pathogens; loss of aquatic diversity; a shift to pollution-tolerant biota; public health problems (Frumkin et al. 2002, Gaffield et al. 2003); and general degradation of water quality (Makepeace et al. 1995).

This chapter discusses solutions for stormwater control, with a specific focus on rain gardens; performance studies and modeling of rain gardens; and background information about a rain garden on the University of Georgia campus.

The rise of Low Impact Development

Traditional management of stormwater originated as flood control, trying to move runoff into receiving water bodies or detention areas as quickly as possible, with little regard to improving water quality (Prince George’s County 1999). Low Impact Development (LID), also known as green infrastructure, is a relatively new style of managing stormwater, popularized in the early 1990s by Prince George County in Maryland (Dietz 2007), that strives to mimic pre-development hydrology by increasing pervious surfaces and infiltration. This increase in infiltration through soils generally provides water quality benefits in addition to controlling quantity and timing of runoff.

Figure 1.1 gives a description of several common types of green infrastructure. The simplest of these techniques is disconnection, redirecting runoff to pervious areas rather than to storm drains. Rain harvesting reduces runoff volume by detaining roof runoff for later use, often for irrigation. Green roofs reduce runoff volume and slow its release by detaining small volumes of water on a vegetated roof, allowing some of the water to be taken up by plants, transpired, or evaporated. Rain gardens, also known as bioretention cells, are depression areas that allow water to infiltrate into amended soil and support vegetative growth. Street planters, infiltration trenches, and porous pavement play similar roles to rain gardens in providing runoff with access to infiltrate underlying soil. Constructed wetlands provide wildlife habitat and are prized for their ability to remove nitrate and break down complex contaminants such as pharmaceuticals (Matamoros & Bayona 2006).

Which LID option to select depends on available land use and budget, as each is best-suited to certain applications; for instance, green roofs are a natural choice for use in cities where land is scarce, porous pavers are a good choice in parking lots, and rain gardens can be used in urban or suburban settings that might traditionally have been covered in pavement or turf grass.

LID techniques vary in how effective they are with regards to infiltration and evapotranspiration (ET) percentages. However, as impermeable surfaces only allow a small fraction of runoff to infiltrate or evaporate, any LID is generally better than no LID.

Green Infrastructure Practice	Description
 Disconnection	Disconnection refers to the practice of directing runoff from impervious areas such as roofs or parking lots onto pervious areas such as lawns or vegetative strips, rather than directly into storm drains.
 Rain Harvesting	Rain harvesting systems collect runoff from rooftops and convey it to a cistern tank where the water is available for uses that do not depend on potable water, like irrigation.
 Rain Gardens	Rain gardens are shallow depressions filled with an engineered soil mix that supports vegetative growth. They are designed to store and infiltrate captured runoff, and retain water for plant uptake. They are commonly used on individual home lots to capture roof runoff.
 Green Roofs	Green roofs (also known as vegetated roofs or ecoroofs) are vegetated detention systems placed on roof surfaces that capture and temporarily store rainwater in a soil medium. They typically have a waterproof membrane, a drainage layer, and a lightweight growing medium populated with plants that absorb and evaporate water
 Infiltration Trench	Infiltration trenches are gravel-filled excavations that are used to collect runoff from impervious surfaces and infiltrate the runoff into the native soil. Some systems are designed to filter runoff and reduce clogging by routing water across grassed buffer strips.
 Street Planters	Street planters are typically placed along sidewalks or parking areas. They consist of concrete boxes filled with an engineered soil that supports vegetative growth. Beneath the soil is a gravel bed that provides additional storage as the captured runoff infiltrates into the existing soil below. Street planters also can be designed with underdrains to avoid ponding on sites with inadequate infiltration capacity.
 Porous Pavement	Permeable pavement and paver systems are excavated areas filled with gravel and paved over with a permeable concrete or asphalt mix. They may also be overset with a layer of pavers. Rainfall passes through the pavement or pavers into the gravel storage layer below where it can infiltrate at natural rates into the site's native soil.
 Constructed Wetland	Constructed wetlands are artificial wetlands, created with a pervious filter bed and heavily planted. They can provide habitat for wildlife and are often used for treating stormwater and municipal wastes. Long residence time of water within the wetland can lead to the removal of nitrate, phosphorus, and even complex pharmaceutical chemicals.

Figure 1.1. Different types of LID (modified from USEPA 2014b)

Rain gardens will be the focus of the remainder of this thesis due to their effectiveness, cost, and design flexibility, as described in the following section.

Rain gardens for stormwater control

Rain gardens are an effective LID tool to mitigate the negative impacts of stormwater on urban streams by reducing peak runoff flows and filtering out pollutants and sediments before they reach the stream. First developed in the 1990s in Prince George's County, Maryland, rain gardens consist of a patch of augmented soil downhill of a runoff source and are a form of bioretention (Roy-Poirier 2010); they slow the flow of runoff and give it a chance to soak into the soil. After infiltrating the soil, water can be taken up by plants on the garden's surface or percolate to deeper depths and eventually make its way into groundwater or nearby streams. The soil is generally prepared by being dug up, mixed with organic matter and sand, and backfilled into the original hole. To ensure there is never a standing pool of water for more than the conventionally-accepted 24-48 hours, some rain gardens are constructed with a tile drain system deep in the soil beneath the garden.

Native plants are a good choice for rain gardens because they tend to be most tolerant of the climate and environmental conditions at a given site (Diekelmann & Schuster 2002). Plants should be somewhat drought-tolerant as well as saturation-tolerant, and they can be selected to give additional benefits such as attracting pollinators or providing wildlife habitat.

Rain gardens are fairly cost-effective, with costs varying based on design choices and averaging between $3-$10 per square foot (Iowa Stormwater 2008, Bannerman & Considine 2003). Design of rain gardens is flexible; because soil can be augmented or added, they need only be situated downhill of a runoff source. Rain gardens can be any size, though thorough treatment of runoff requires some calculations of drainage area and anticipated discharge. They are generally capable of treating runoff from a drainage area three to ten times the surface area of the garden itself, but this treatment capacity is dependent on the garden media and depth (Bannerman & Considine 2003). While many stormwater installations require the involvement and supervision of an engineer or landscape architect, rain gardens can be designed and installed by any homeowner.

Performance studies

Performance studies show rain gardens as being consistently effective in reducing peak flows, runoff volumes, and pollutants. The compiled results of four of these studies show a general pattern of rain gardens decreasing heavy metals (Dietz 2007). Additional studies quantify nutrient, pathogen, and flow control. A controlled laboratory study used soil column experiments and small-scale bioretention boxes to measure metal sorption capacities at varying pH levels (Davis et al. 2001). These experiments showed reductions in copper, lead, zinc, phosphorus, total Kjeldahl nitrogen (TKN), and ammonium, with small reductions or increases in nitrate. A bioretention cell draining parking lot runoff in Charlotte, North Carolina, found reductions in ammonium, total nitrogen, TKN, phosphorus, total suspended solids (TSS), zinc, copper, lead, fecal coliform, and E. coli; an average 99% decrease in peak flow; but increases in nitrate and iron (Hunt et al. 2008). Differences in climate, soil, and design account for the different removal rates found in lab and field studies across the country. Even in the arid and semi-arid regions of the western United States, rain gardens are effective where their designs incorporate sandier, drier soils and xeric plants unsuitable for eastern sites (Steffen 2012).

Rain gardens exhibit less consistent behavior with regard to nitrate reductions. In fact, low nitrate reduction and even sometimes nitrate export are common findings in evaluations of bioretention areas. US Environmental Protection Agency (USEPA) lists the results from a few case studies detailing this finding (2000). A combined laboratory and field study of a mall parking lot in Beltline, Maryland, found that bioretention areas can almost entirely sequester metals such as copper, lead, and zinc but at the same time perform poorly with regard to nitrate. A large-scale laboratory plot increased nitrate levels 100-200%, while the actual mall field site decreased nitrate by 16%. Another parking lot in Landover, Maryland, saw decreases in nitrate of 15% and slightly lower removal of copper, lead, and zinc, around 50%.

Poor removal of nitrate by bioretention is surmised to be due to the process of nitrification. Nitrification occurs when ammonium is transformed by soil microbes into nitrite and then nitrate; such a process occurs in aerobic conditions. Conversely, denitrification occurs when microbes engage in anaerobic decomposition, transforming nitrate to a reduced form of nitrogen – N_2 gas (Stevenson & Cole 1999). This process occurs in a low oxygen environment. Consequently, low denitrification rates and thus high nitrate are generally found in unsaturated soils where a constant source of oxygen is available (Gomez et al. 2012). Because rain gardens are generally designed to promote good drainage and prevent standing bodies of water, they frequently have unsaturated soils and exhibit higher nitrification than denitrification rates. Denitrification in rain gardens can be promoted through several techniques, most of which endeavor to create saturated conditions and increase the residence time of water in the bioretention cell (Kim et al. 2003, Hunt 2003).

A rain garden’s performance may vary over the course of its lifespan. Over time pollutants accumulate in the soil, the soil media settles, and clogging can occur in the soil or underdrain system (Li & Davis 2008). Thus, one evaluation study is simply not enough to tell if the garden is successful at improving downstream water quality; multiple follow-up studies should be conducted, particularly to discover when a rain garden has outlived its usefulness and can no longer sequester pollutants.

Multiple rain garden or LID installations in a given area can achieve large-scale stormwater improvements. Comparisons of traditional subdivision designs with subdivisions employing multiple LID installations showed that the LID subdivisions were able to maintain a post-development hydrologic regime similar to their pre-development one (Dietz & Clausen 2008). Such watershed-scale efforts are not confined to the United States: the Little Stringybark Creek Project in Australia is a catchment-scale effort to replace typical “grey” stormwater infrastructure with green LID and examine the water quality improvements downstream. This project transformed 6% of a watershed’s impervious surfaces to bioretention through the use of economic incentives to homeowners (Bos et al. 2009).

Performance modeling

While direct monitoring of a rain garden or bioretention cell gives valuable information about the status of the site, such monitoring is not always possible, whether due to time, money, or sheer size as with watershed-scale installations. Modeling is an appropriate way to estimate bioretention performance without physically monitoring a site. Models are developed based on the underlying physical processes of a rain garden, calibrated with actual measured data, validated against additional measured data, and can then be used to estimate measurements for unmonitored time spans or sites. Some researchers simply turn to the classical mathematics of hydrology to determine reductions in runoff using LID at the watershed scale (Liu et al. 2014). Many others turn to complex software modeling systems. There is no shortage of models to use for simulating rain gardens and their performance. An online bibliographic database search revealed 178 hydrologic models in use, varying in age and pervasiveness of use (Brewer 2014).

Soil-level models are appropriate for quantifying the impacts of rain gardens on the quantity and quality of water that passes through them. Several models solve the Richards equation to estimate flow through a rain garden, including RECHARGE (Dussaillant et al. 2004) and SWIMv1 (Scientific Software Group 2014). RECARGA is an offshoot of RECHARGE that uses the Green & Ampt equation for infiltration in place of Richards equation (Dussaillant et al. 2005). COMSOL solves the Richards 2D equation to more accurately model a rain garden cell (He & Davis 2011).

HYDRUS is appropriate for one-, two-, or three-dimensional models and numerically solves the Richards and Advection-Dispersion equations to simulate the flow and storage of water, heat, and nutrients through soil media (Simunek et al. 2005). HYDRUS uses precipitation input and is calibrated with soil data such as fill type, hydraulic conductivity, bulk density, and vegetation cover. HYDRUS can model one-dimensional (1D) soil columns or 2D and 3D rain gardens, providing modelers with the ability to simulate differences in bioretention design and fill. In a study in Athens, Georgia, HYDRUS-1D was successfully used to model peak flow and retention of stormwater by green roofs and was then validated against several experimental green roofs (Hilten et al. 2008). HYDRUS-3D was used to model flow through a bioretention site in semi-arid Utah, but the model ultimately had trouble converging on a solution when soils with vastly different hydraulic characteristics were situated immediately next to one another (Steffen 2012).

Measuring the effects of many LID installations across a watershed is more difficult to accomplish than monitoring a single rain garden, so watershed modeling is particularly useful in these watershed-scale cases. DRAINMOD bridges the gap between local and watershed-scale with its distributed treatment of LID practices. Originally developed for agricultural use in modeling tile drain systems, DRAINMOD has been used to simulate LID effects on hydrology in urban settings with high accuracy (Brown et al. 2013).

A comprehensive guide of watershed-modeling software reveals that a number of models are decent options for quantification of LID effects on water quality at the catchment or watershed scale (Beckers et al. 2009). Each model has its own specialty for which it was originally developed, but many have been used to successfully simulate the performance of catchment-level LID installations. The Army Corps of Engineers' HEC-HMS tool has been used to simulate watershed-scale impacts of a network of retention basins in Pennsylvania (Emerson et al. 2005). This study found that grey infrastructure detention basins had little impact on the watershed flow regime, despite individual basins being able to control large storm events. The authors advocate the use of runoff volume attenuation techniques, a category under which LID installations fall.

EPA's tool SWMM (Storm Water Management Model) is particularly useful for modeling hydrology in urban environments, as it takes into account stormwater runoff, water storage, and sewer systems. SWMM also includes modules for urban LID installations, including bioretention cells, vegetated swales, and rainwater cisterns. It was used to model the reductions in runoff peak flow and volume due to the addition of green roofs to two blocks in the Bronx, New York (Khader & Montalto 2008). Watershed-scale installations of LID in an urban Texas watershed were simulated with a combined HEC-HMS and SWMM setup and found that LID could potentially provide better control than traditional grey infrastructure of frequent, small storms (Damodoram et al. 2010).

RHESSys is a so-called hydro-ecological model that simulates ecological properties as well as hydrology; it can be used to simulate daily flux and transport of carbon and nitrogen in a modeled catchment. A preliminary study of streamflow and stream chemistry for a small forested watershed in the Baltimore Long-Term Ecological Research site was conducted using RHESSys (Tague & Band 2004). The model simulated baseflow well and successfully captured the temporal pattern of nitrate production, though the exact predictions of runoff peaks and nitrate concentrations would have benefited from better calibration. Soil Water Assessment Tool (SWAT) is a flexible hydrologic model that simulates watershed hydrology and water quality (Gassman et al. 2007). Its built-in LID modules can be used to model impacts of land use change on discharge and nutrients. A study in the Upper Cohansey watershed in New Jersey used SWAT to model the impacts of filter strips, bioretention ponds, and constructed wetlands on phosphorus removal at a watershed outlet (Rutgers Extension 2009). The model's discharge was calibrated and validated against a US Geological Survey (USGS) stream gauge and exhibited acceptable results based on calculated Nash-Sutcliffe efficiency values.

UGA's Lily Branch rain garden

The University of Georgia has installed several dozen rain gardens across its campus, including one along Lily Branch (UGA 2014). Lily Branch is a stream heavily impacted by stormwater, with its headwaters in the urban Five Points area of Athens, Georgia, from whence it flows just over a mile before joining the North Oconee River. About a third of that journey is culverted, buried in a concrete channel as it flows through the UGA campus from the Foley Field baseball stadium to the Lamar Dodd Art School on East Campus. The stream's location and surrounding drainage basin is shown in Figure 1.2. Historically, it has seen inputs that include leaking sewer lines, sedimentation from construction, and leaking gasoline tanks (Spalding 2012). The legacy of pollutant inputs from surrounding urban land use include high fecal coliform numbers and high conductivity (UOWN 2014).

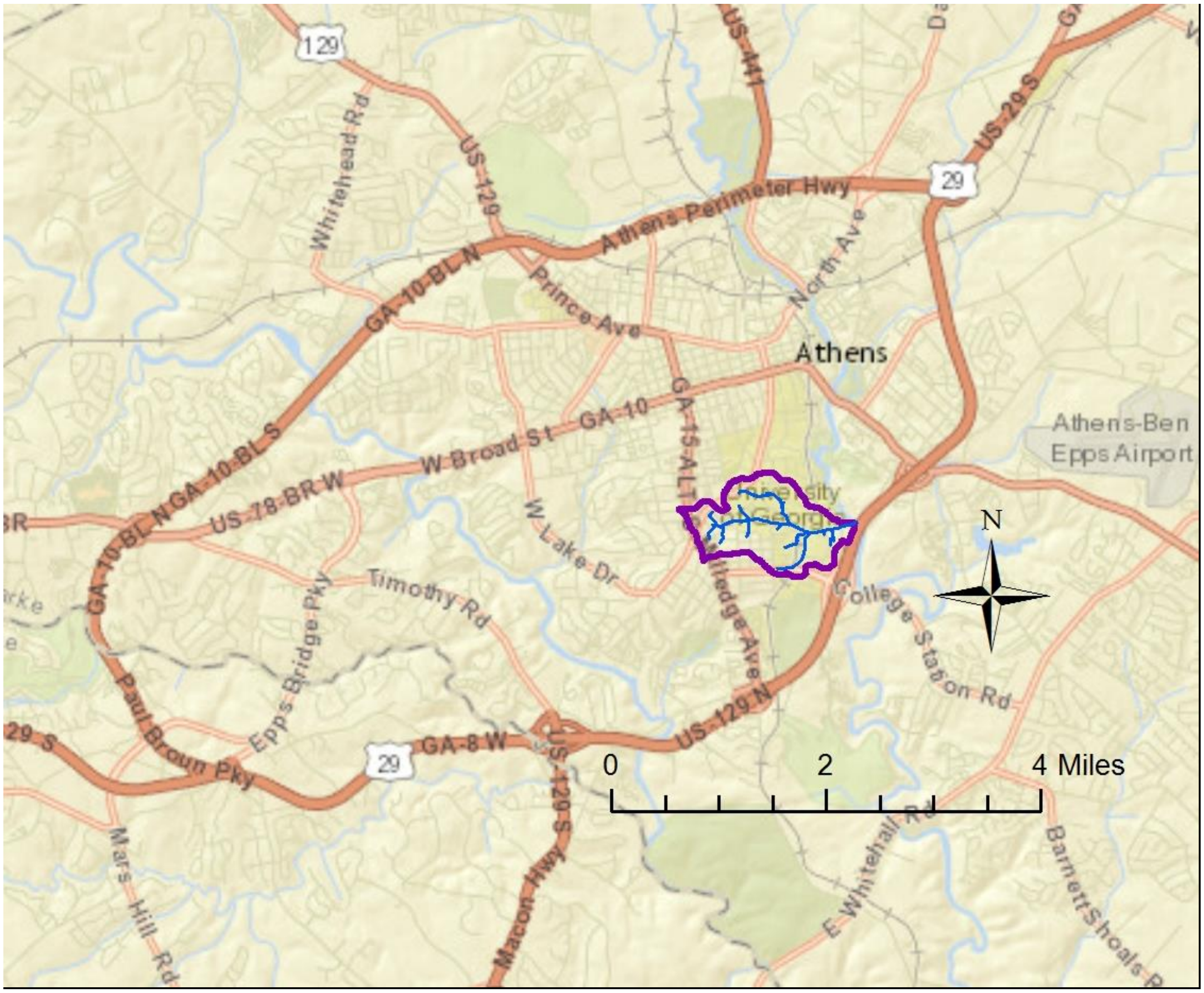

Figure 1.2. Lily Branch in Athens, Georgia. Drainage basin shown (purple) around stream (blue).

The surrounding 397-acre watershed contains a large percentage of impervious surfaces, as well as numerous apartment complexes, houses, parking lots, and even a basketball coliseum. The land use for Lily Branch watershed, shown in Figure 1.3, is primarily urban, with high-density urban use (URHD) comprising 27.31% of the watershed, medium-density land use (URMD) 42.06%, and low-density use (URLD) 21.29%. Additionally, industrial use (UIDU) accounts for 4.99%, and deciduous forest (FRSD) and forested wetland (WETF) account for 3.12% and 1.22%, respectively.

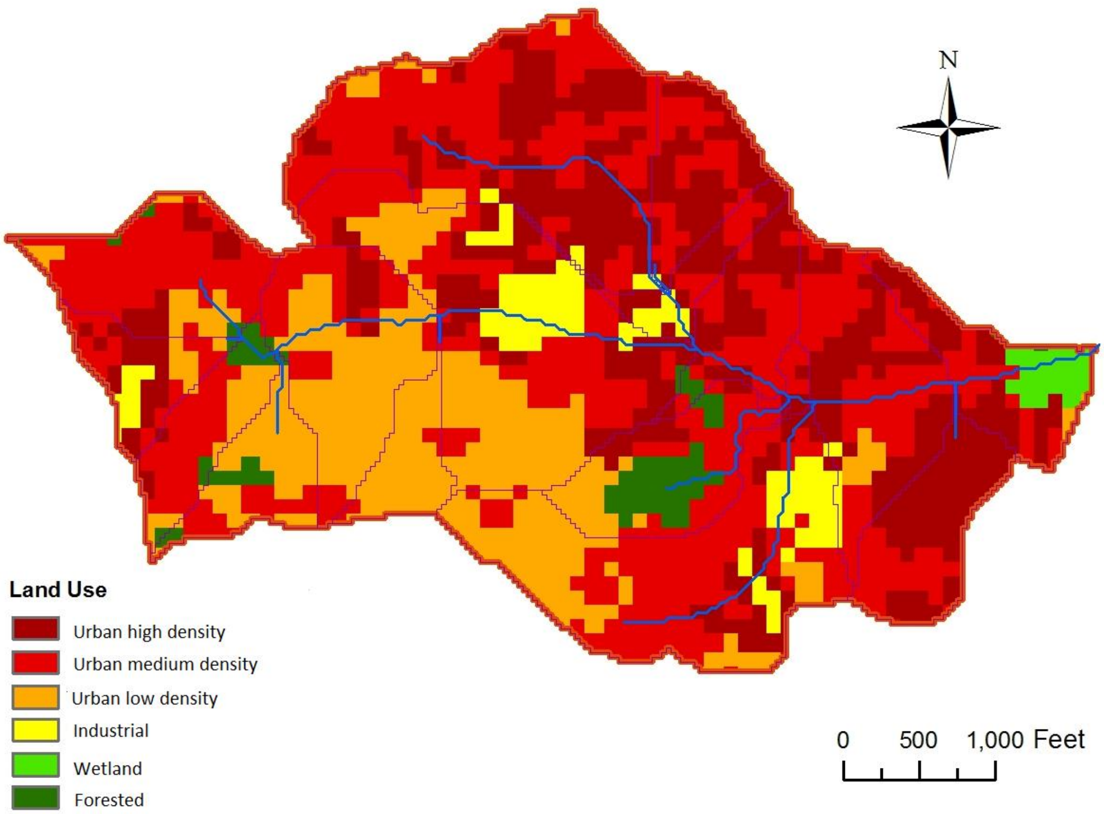

Figure 1.3. Land use for delineated Lily Branch watershed

A large rain garden is located on the East Village campus, outlined in red in Figure 1.4, and intercepts water from a parking deck and several buildings before they flow into Lily Branch.

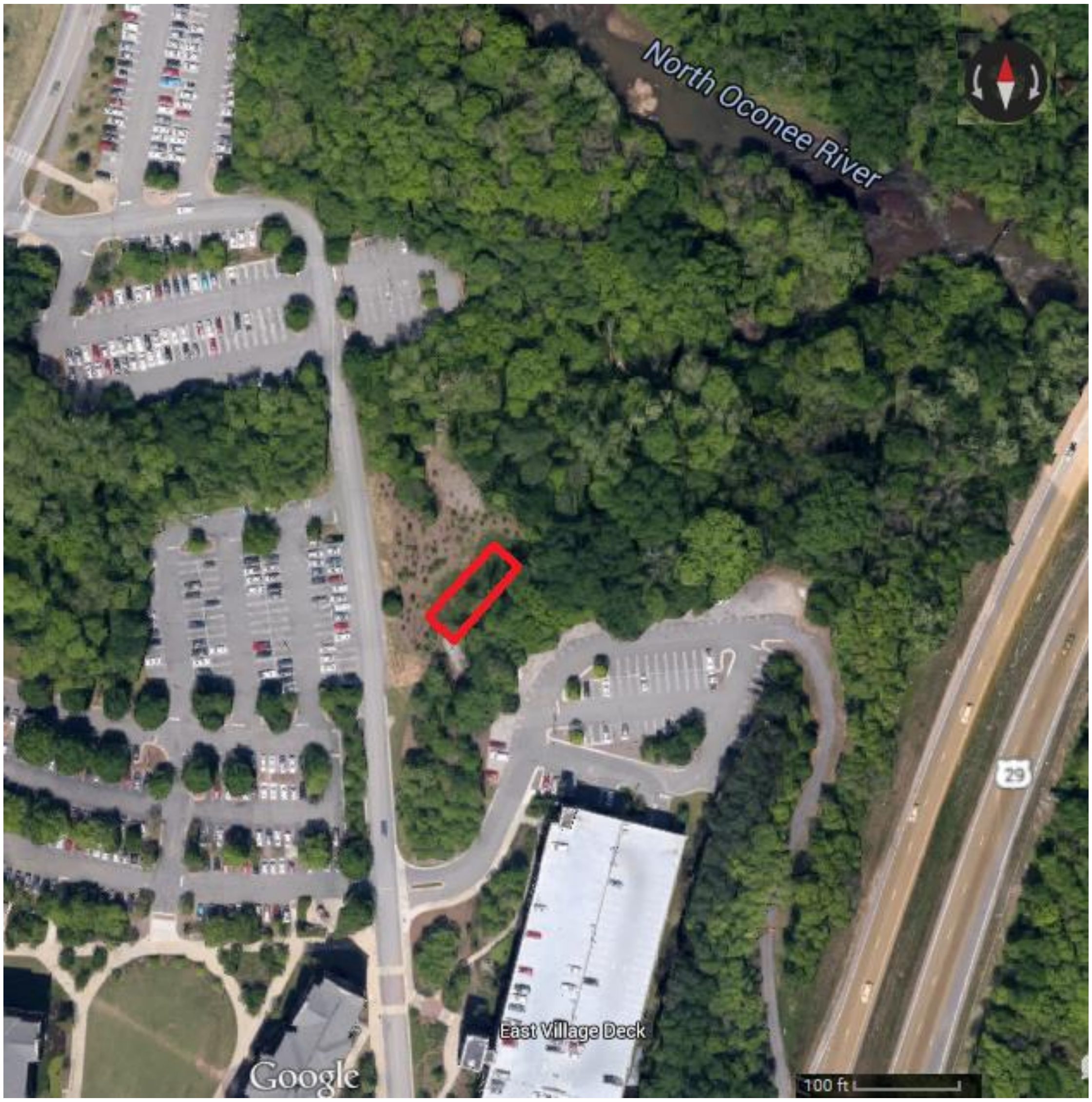

Figure 1.4. Location of Lily Branch rain garden, outlined in the red box

Evaluation to determine the success of restoration and rehabilitation projects such as rain gardens is often neglected (Palmer et al. 2005). UGA's rain gardens are no exception, as the Lily Branch rain garden is the only rain garden or bioretention cell on campus that has been evaluated to ensure that it is actually working as anticipated. This rain garden was outfitted to monitor the quantity and quality of the water that passes through it and subsequently is an ideal subject for a study on its effectiveness at treating stormwater.

From 2011 to 2013, a master's student in the Department of Crop & Soil Sciences, Kathryn Shepard, monitored the Lily Branch rain garden to determine whether it was successfully reducing peak flows and pollutant concentrations. Her results showed that peak flow was reduced, along with several pollutants such as zinc, BOD, and ammonium, but that nitrate was increased by the garden (Shepard 2013).

While nitrate is a crucial nutrient for plants, excessive concentrations of nutrients can contribute to eutrophication downstream, particularly once a stream reaches a lake, reservoir, or the ocean. This influx of nutrients to a lentic water body can cause algal blooms which eventually die and are decomposed by microbes. The process of microbial respiration removes oxygen from the water and can create anoxic conditions, which cause harm to aquatic biota. Thus, a rain garden that is leaching nitrate might contribute to the degradation of surface waters, which is generally opposite to the motivation behind its installation. The cause of the high nitrate concentrations exiting this rain garden was posited to be the organic matter that was originally mixed into the garden's soil media (Shepard 2013), but as explained in the performance studies section above, nitrate export is actually a common problem to rain gardens.

Shepard measured concentrations of pollutants but did not quantify pollutant loads, that is, how much of each pollutant actually discharged into Lily Branch. This thesis answers the question of whether nitrogen, phosphorus, and sediment loads into Lily Branch are decreased by the rain garden. I measured pollutant concentrations from storm events; measured hydrologic parameters and used them to calculate pollutant loads; and measured soil parameters related to infiltration and used them to determine whether the garden is uniformly detaining water throughout its bed. Such findings could determine necessary modifications for the Lily Branch rain garden or guide the design and installation of future campus rain gardens. Further, it is important to understand the impacts that increased numbers of rain gardens can have on campus stream water quality and if there is an ideal number of rain gardens to install ultimately. I conducted watershed-scale modeling of hydrology in an initial attempt to understand collective impacts of campus rain gardens.

The remainder of this thesis is organized into three chapters. Chapter 2 describes the process of monitoring the Lily Branch rain garden. I discuss results for measured nitrogen and phosphorus loads, as well as for TSS and hydrologic regime. I also present hydraulic conductivity and soil moisture data and discuss their relation to the rain garden’s infiltration capabilities. Chapter 3 describes watershed-scale modeling of the Lily Branch watershed conducted using SWAT. This modeling attempts to quantify how much runoff in a watershed must be treated by rain gardens before seeing a visible reduction in peak flows due to stormwater. Chapter 4 describes perceived barriers or difficulties in rain garden installation. It also discusses the role of state-based stormwater codes in encouraging LID as well as recent steps taken by the state of Georgia to make such installations more prevalent.

CHAPTER 2

MONITORING THE LILY BRANCH RAIN GARDEN

From 2011 to 2013, the Lily Branch rain garden was monitored by a Crop & Soil Sciences master's student to determine whether the garden was successfully reducing peak flows and pollutant concentrations. Her results showed that peak flow was reduced, along with zinc, biochemical oxygen demand (BOD), and ammonium, but that nitrate was increased by the garden (Shepard 2013). This thesis chapter details research to determine if the rain garden is reducing loads of nitrogen, phosphorus, and sediment. These pollutants are of particular interest because sediments are one of the top pollutants of US streams, and nitrogen and phosphorus from runoff can contribute to eutrophication issues downstream. The chapter also presents data about the garden's infiltration capabilities and soil moisture content.

Site description

The Lily Branch rain garden is a 375 m^2 bioretention cell located at the University of Georgia East Campus Village, with location shown in Figure 2.1. The garden was installed in October 2010 by external contractor Erthworks. Runoff from a 3,500-m^2 parking deck and lot is channeled into the garden via a culvert and is held behind a rectangular weir 22.5 cm in height. When the weir overflows, water spills down a channel of large gravel aggregates, shown in Figure 2.2, before it reaches the bed of the garden itself, which is 30.5 m long and 12.3 m wide. Erosion rills are visible in several locations around the sides of the garden, suggesting that additional runoff flows into it from a nearby street, but that extra inflow has not been quantified.

At the garden bed, the runoff infiltrates into the soil, passing through 1.22 m of fill media and a geotextile layer before reaching a perforated tile drain system beneath the garden. The 15-cm diameter drain pipes are surrounded by 20 cm of pea gravel. Water that flows into the pipe ultimately passes through the garden's outflow and then into the small stream Lily Branch. The garden outflow is outfitted with a 90-degree notch triangular weir whose notch is 8 cm off the ground. The garden's inflow and outflow weirs are shown in Figure 2.3.

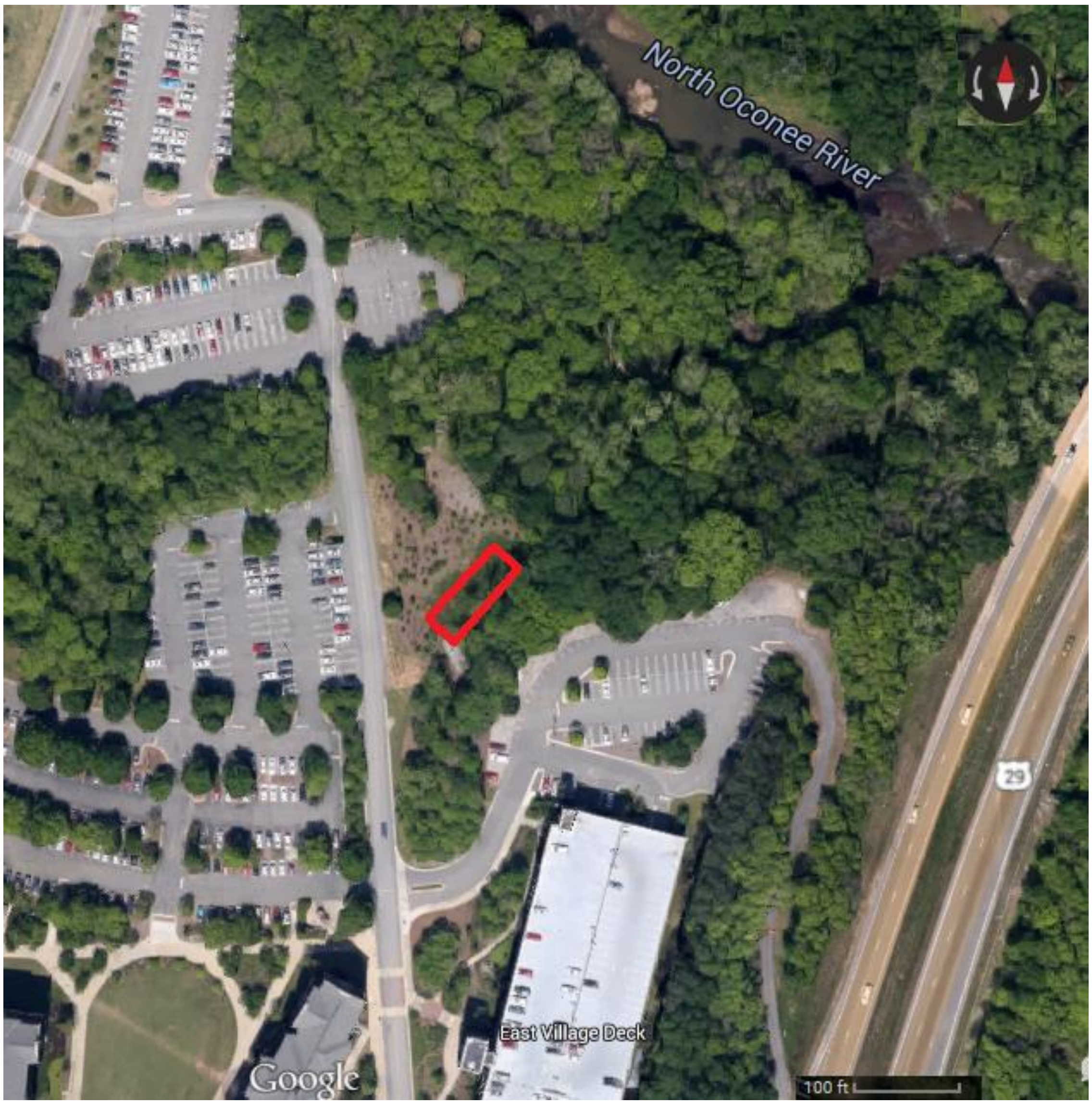

Figure 2.1. Map of Lily Branch stream and rain garden (outlined in red)

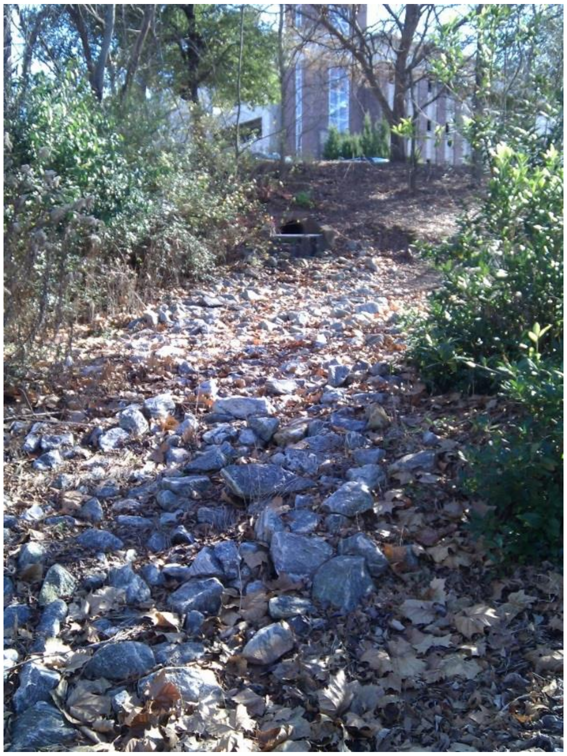

Figure 2.2. Inflow of rain garden, shown with parking garage in background and energy-dissipating gravel aggregates in foreground.

Figure 2.3. Inflow and outflow weirs (credit: Kathryn Shepard). The inflow weir is 112 cm wide and 22.5 cm high. The outflow weir is a 90-degree notch triangular weir. The point of the triangle is 8cm high, and the weir extends across the width of the outflow pipe opening.

A standpipe 15 cm in height near the garden's outflow end accommodates large storm events and ensures that there is never a long-standing pool of water on the surface of the rain garden. This standpipe directs overflow water straight into the perforated pipe, bypassing the soil media and along with it the pollution- and peak flow-reducing benefits of the garden. Figure 2.4 shows a cross-sectional view of the garden. The fill media is a loamy sand consisting of 89% sand, 9% silt, and 2% clay.

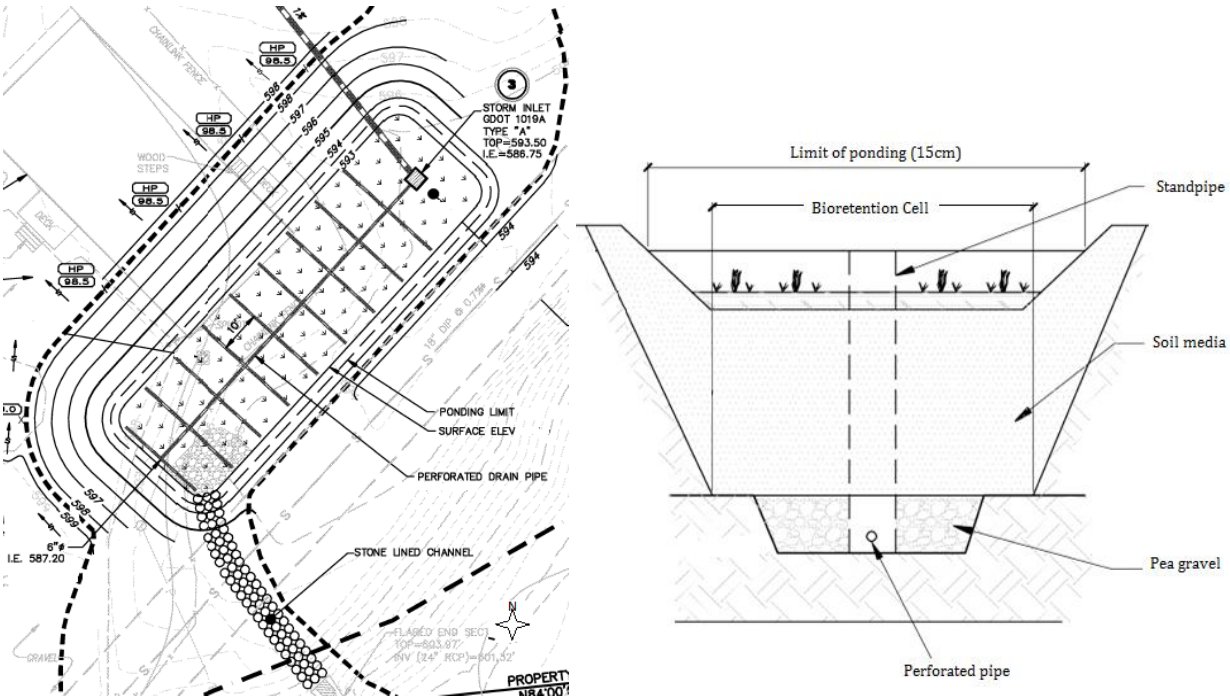

Figure 2.4. Planform and cross-sectional views of garden (credit: UGA Architects)

Methods

Two automated ISCO 6712 water samplers were placed in the garden when it was first installed, with one at each of the inflow and outflow weirs of the rain garden. I programmed both samplers to begin taking water samples during storm events when water reached a given standing height behind the respective inflow and outflow weirs, as measured every two minutes by ISCO 720 submerged flow module pressure transducers.

Sample collection triggered when water reached a certain height behind each weir, signaling that a storm event was occurring, and then all 24 of the 350-mL bottles in the ISCO filled automatically based on set parameters for the weir. The inflow ISCO triggered sampling at levels of 0.15 m and pulled new samples every 10 minutes for four hours, while the outflow ISCO triggered at 0.08 m and sampled every 30 minutes for 12 hours. The differences in trigger levers and time frequency were chosen to account for the observed lag between the garden inflow's "first flush" of runoff, or high peak discharge resulting from the onset of a precipitation event, and runoff reaching the outflow after its prolonged, slowed passage through the garden.

I collected the sample bottles within 24 hours of a storm event and prepared composite samples for the inflow and outflow by combining 20 mL aliquots from each individual bottle. I immediately stored the samples in a freezer until I could process them.

Total Suspended Solids (TSS) were measured by freeze-drying the individual samples using the University of Georgia Analytical Chemistry Laboratory's (ACL) Virtis Freezemobile. I loosened the caps on each of the 20 mL sample bottles and placed them in the freezer for a week until all the water had evaporated from the bottles. I then weighed the remaining solids using a mass balance.

To measure total nitrogen and total phosphorus, I performed a digestion on the composite samples, mixing five mL of each unfiltered composite sample with one mL of persulfate reagent to transform all forms of nitrogen and phosphorus into soluble form. I mixed the test tubes thoroughly using a vortex and transferred the samples to the ACL staff, who autoclaved them and analyzed them for total nitrogen (Total N as NO_3-N) and total phosphorus (Total P as PO_4-P) using automated colorimetry techniques (Qualls 1989). ACL staff also measured soluble reactive phosphorus (PO_4-P, referred to hereafter as SRP), ammonium (NH_4-N), and nitrate (NO_3-N) concentrations from the filtered composite samples using the following respective standard methods: Automated Ascorbic Acid Reduction Method, Automated Phenate Method, and Automated Cadmium Reduction Method.

I also collected individual samples from each of the 48 bottles for several storms and analyzed them to verify that concentrations of pollutants are highest during a storm's "first flush," the quick, large peak of runoff generated at the start of a precipitation event. I measured TSS for every individual sample across four storms and nitrate for the first 12 samples at both the inflow and outflow for two storms.

Infiltration is crucial to a rain garden's ability to reduce pollutant loads, allowing pollutants to sorb to the soil or be taken up by plant roots. To gain an understanding of how well infiltration is occurring throughout the rain garden, I measured soil moisture and saturated hydraulic conductivity throughout the garden. Moisture and temperature sensors collected continuous data about soil in different locations and depths of the garden. With the help of several graduate students, I installed four Em50 dataloggers across the garden, each with five Decagon Devices sensors attached to the logger, shown in Figure 2.5.

We placed a logger near the inflow, outflow, and middle of the garden (three "main" loggers), and a fourth logger in the middle of the garden on the side near a previously-installed time-domain-reflectometry (TDR) array that measures soil moisture in a small area of the garden. For each datalogger we augered holes at a depth of 1.01 m, 0.77 m, 0.55 m, and 0.33 m; placed a sensor in each hole; and carefully covered the sensor with displaced soil. We also placed a sensor just under the soil surface at each datalogger. The depths were chosen to match sensor depths of the previously-installed TDR array so that data from the two sources can be compared and combined in the future. The sensors were a mix of models 10HS, 5TM, and 5TE;

all the sensors measured soil moisture content, and some also had the ability to measure conductivity and temperature.

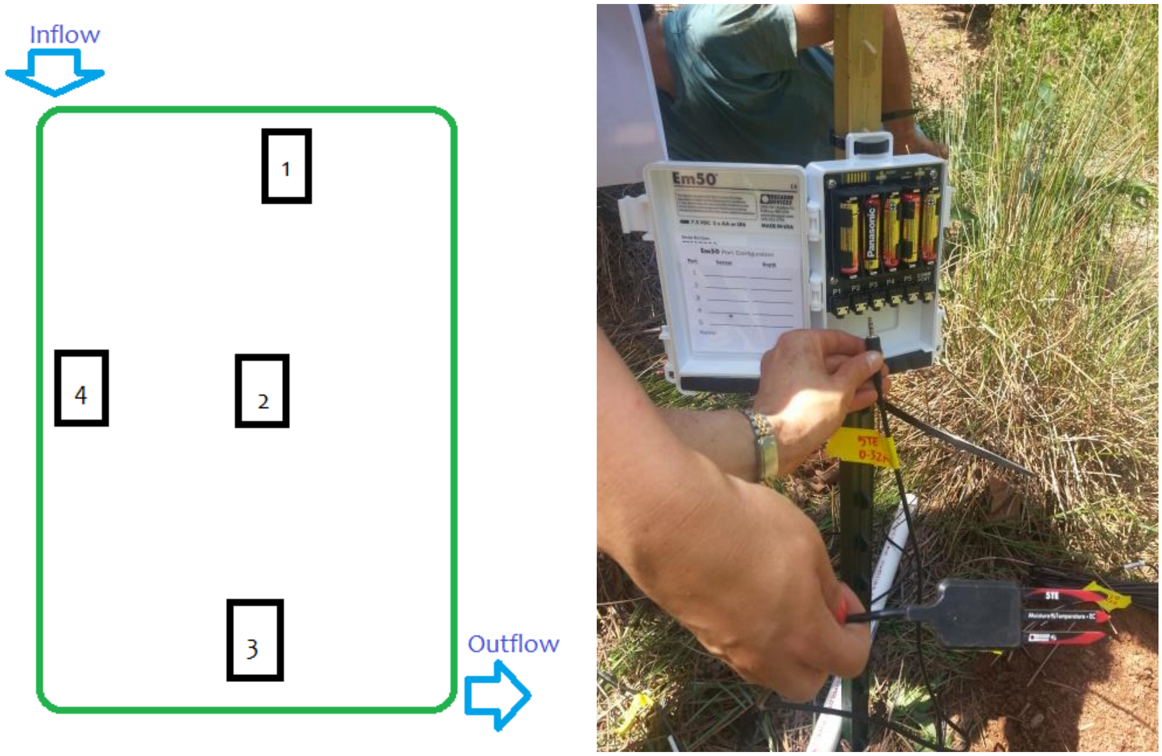

Figure 2.5. Location of dataloggers and a sample logger and Decagon sensor.

Saturated hydraulic conductivity (Ksat) of the soil is the speed at which water percolates downward through the saturated soil media and ultimately controls how much runoff can be infiltrated into a site before the runoff ponds or becomes overland flow. I measured Ksat using an Aardvark permeameter at each of the three “main” Em50 datalogger locations. One Ksat measurement was taken to correspond with each buried Decagon sensor, giving a total of 12 Ksat measurements across the garden. Surface sensors were excluded since the permeameter can only measure Ksat properly when placed into a hole.

To measure Ksat, I first augered a borehole of a given depth corresponding to one of the buried moisture sensors and then placed a permeameter module, consisting of a closed capsule holding a floating ball, into the hole. The module was attached via a long tube to a tank of water sitting atop a scale on a table outside the hole. Actual setup in the rain garden is shown in Figure 2.6. Water flowed from the tank into the soil at a rate dictated by the soil's ability to infiltrate more water. A computer attached to the scale running the SimplyData program recorded the amount of water that flowed into the hole every minute. Ksat values were automatically computed using the Elrick and Reynolds (1992) method after volume readings remained fairly constant. For three successive readings, volume measurements had to fall within a range of one mL of each other to show that infiltration had leveled off and that the saturation point of the soil being reached.

Figure 2.6. Permeameter setup in garden, with close-up of capsule module. The capsule is lowered into an auger hole, and water flows out of it at a rate determined by the infiltration ability of the underlying soil.

Monitoring results

I analyzed hydrographs from each of the ISCOs and calculated storm inflow and outflow discharge and volumes using pressure transducer-measured water levels and the Bernoulli equation for weirs. The analyzed water samples and hydrograph information came from 10 storm events ranging across eight months, from June 2014 to January 2015. Table 2.1 lists the dates and rainfall totals of the storms. Hydrographs were recorded for storms in August and September that would have been substantial enough to trigger collection of all samples at both ISCOs, but equipment problems prevented proper triggering of sample collection. The problems were eventually resolved, and sample collection continued uninterrupted from late September onward.

Table 2.1. Sampled storm event dates and associated rainfall totals

Storm Event	Approximate Start Date and Time	Rainfall total (mm)
1	6/5/2014 21:00	0.36” (9.14)
2	6/23/2014 19:40	0.81” (20.57)
3	7/19/2014 2:00	1.33” (33.78)
4	10/3/2014 11:40	0.3” (7.62)
5	10/14/2014 5:45	1.64” (41.66)
6	11/16/2014 23:55	1.07” (27.18)
7	11/23/2014 4:35	1.55” (39.37)
8	12/16/2014 2:50	0.24” (6.10)
9	12/22/14 17:30	0.47” (11.94)
10	1/23/15 3:20	0.85” (21.59)

The Georgia Stormwater Management Manual requires that rain gardens provide a 24-hour extended release period for the 1-year 24-hour storm event; that is, it must detain the first 1.2 inches of runoff from all storms. The runoff volume generated by 1.2” of rainfall on the parking lot above the rain garden is approximately 106.68 m^3. This volume is called the channel protection volume (CPv); its detention is intended to help prevent channel scouring and erosion. Released over 24 hours, the rain garden should discharge this volume at a rate of 0.00124 m^3/s. According to the Georgia Stormwater Management Manual, channel protection volume requirements are not required for discharges under 0.0566 m^3/s (2.0 ft^3/s), which would exclude this rain garden. The rain garden would also likely be excluded from this requirement because its outflow first meets up with a larger stormwater drain system before flowing into Lily Branch. However, for the sake of demonstration, the garden’s release rates over the 10 measured storms are included in Table 2.2. These release rates are the outflow volume divided by the total measured release time. Half of the storms provided a sufficient 24-hour release period, while the remaining did not, though Storms 2, 6, and 9 were very close to the cutoff. The other two storms that did not meet the requirement were Storms 3 and 7, which corresponded to larger rain events.

Table 2.2. Release rates of outflow volumes

Storm Event	Approximate Release Time (hours)	Release rate (m^3/s)
1	11	0.000711
2	26.5	0.00159
3	32	0.00304
4	13	0.00115
5	16	0.000995
6	5.5	0.00134
7	27	0.00278
8	8	0.000239
9	15	0.00131
10	36	0.000388

The overall volume of runoff flowing out of the garden was reduced by an average of 70%, with individual reductions shown in Figure 2.7. Peak flows were reduced by an average of 91%, shown in Figure 2.8, and the average amount of time between the peak flows at the inflow and outflow monitoring points was 102 minutes, shown in Figure 2.9. Figure 2.10 provides sample hydrographs for Storms 2 through 5 that clearly exhibit the changes in flow regime at the inflow and outflow of the rain garden. Storms 2 and 4 were brief, strong rain events, while 3 and 5 were prolonged storm events. Peak flows and volumes for both types of storms were successfully reduced for the entire course of the storm.

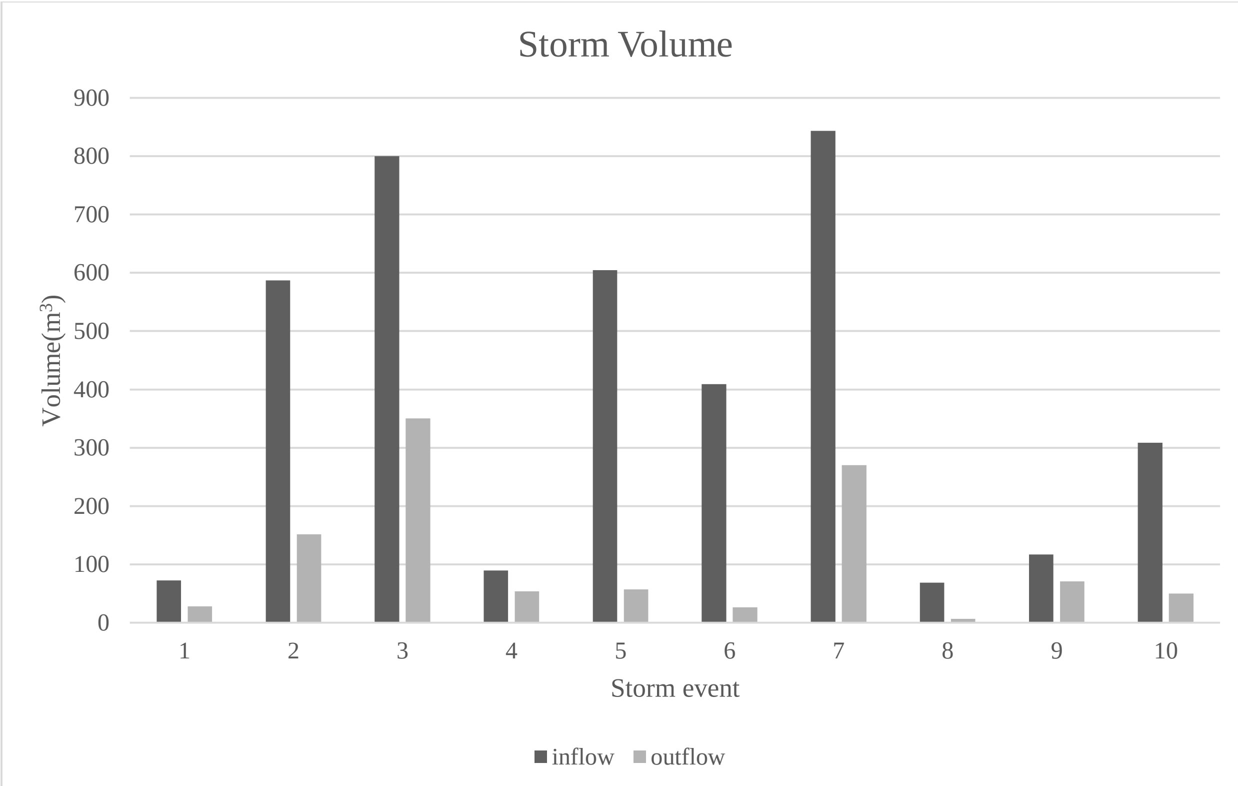

Figure 2.7. Individual volumes of runoff

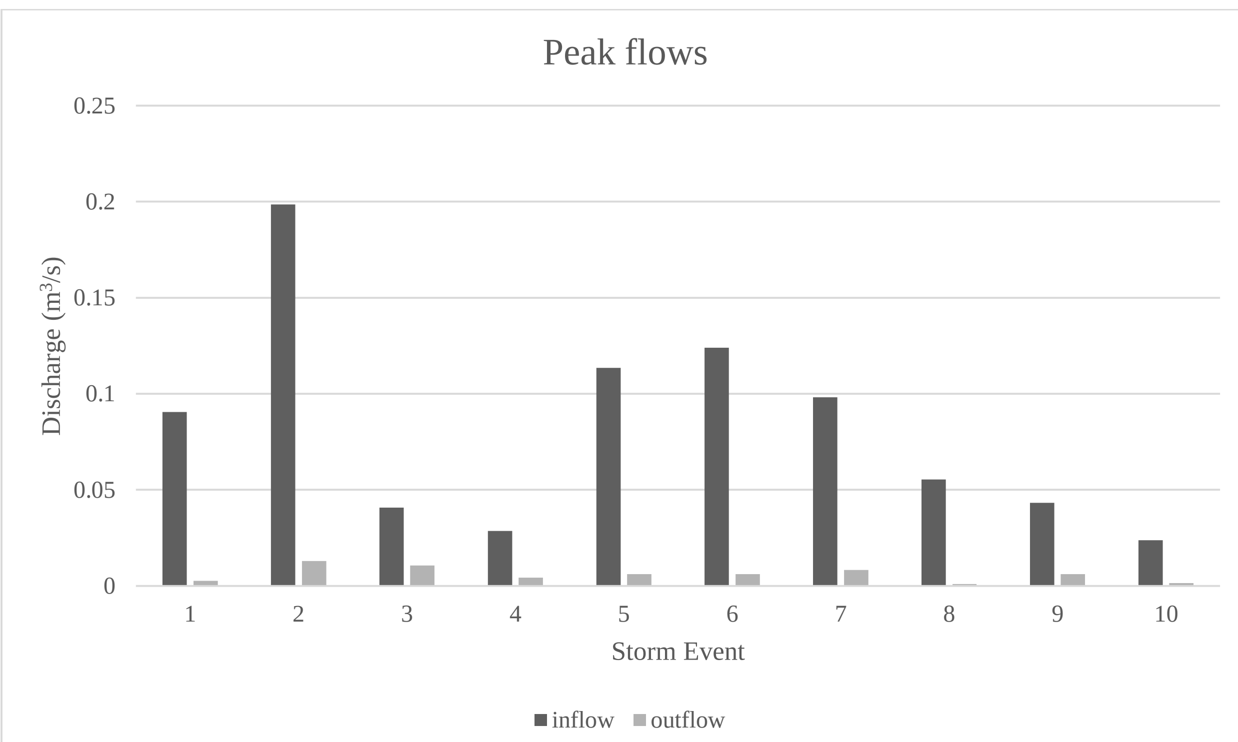

Figure 2.8. Individual peak flows

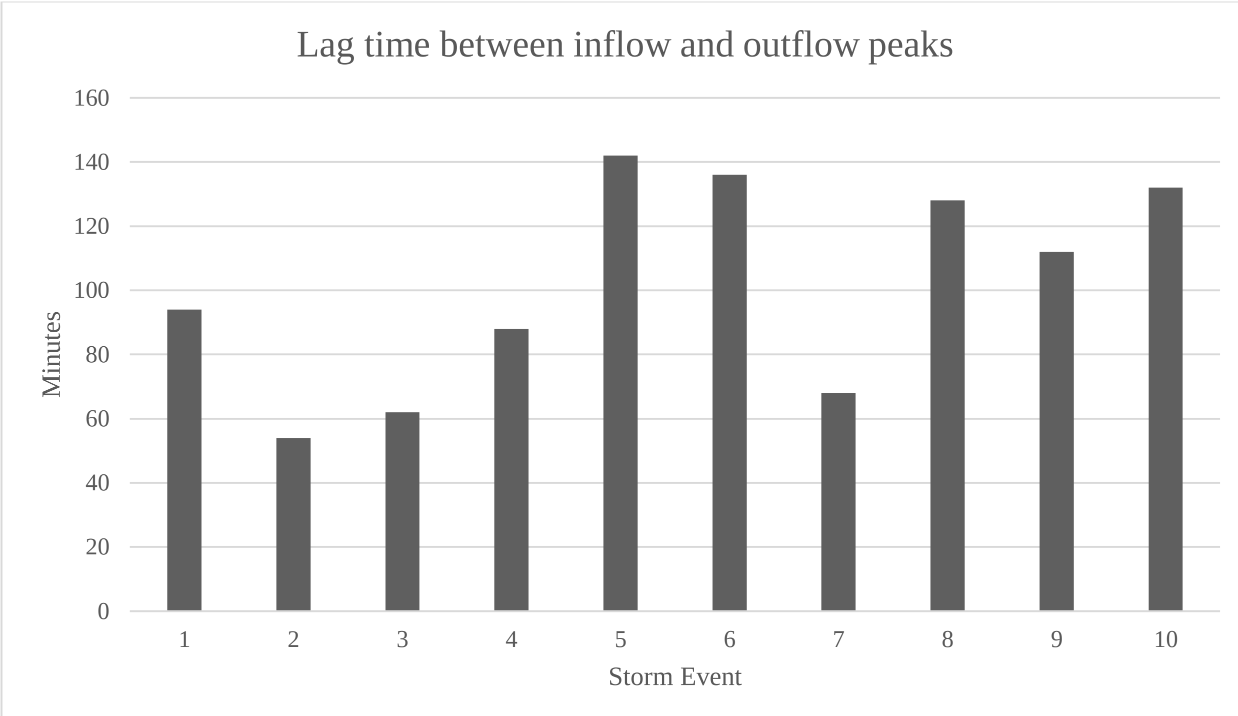

Figure 2.9. Lag times between inflow and outflow

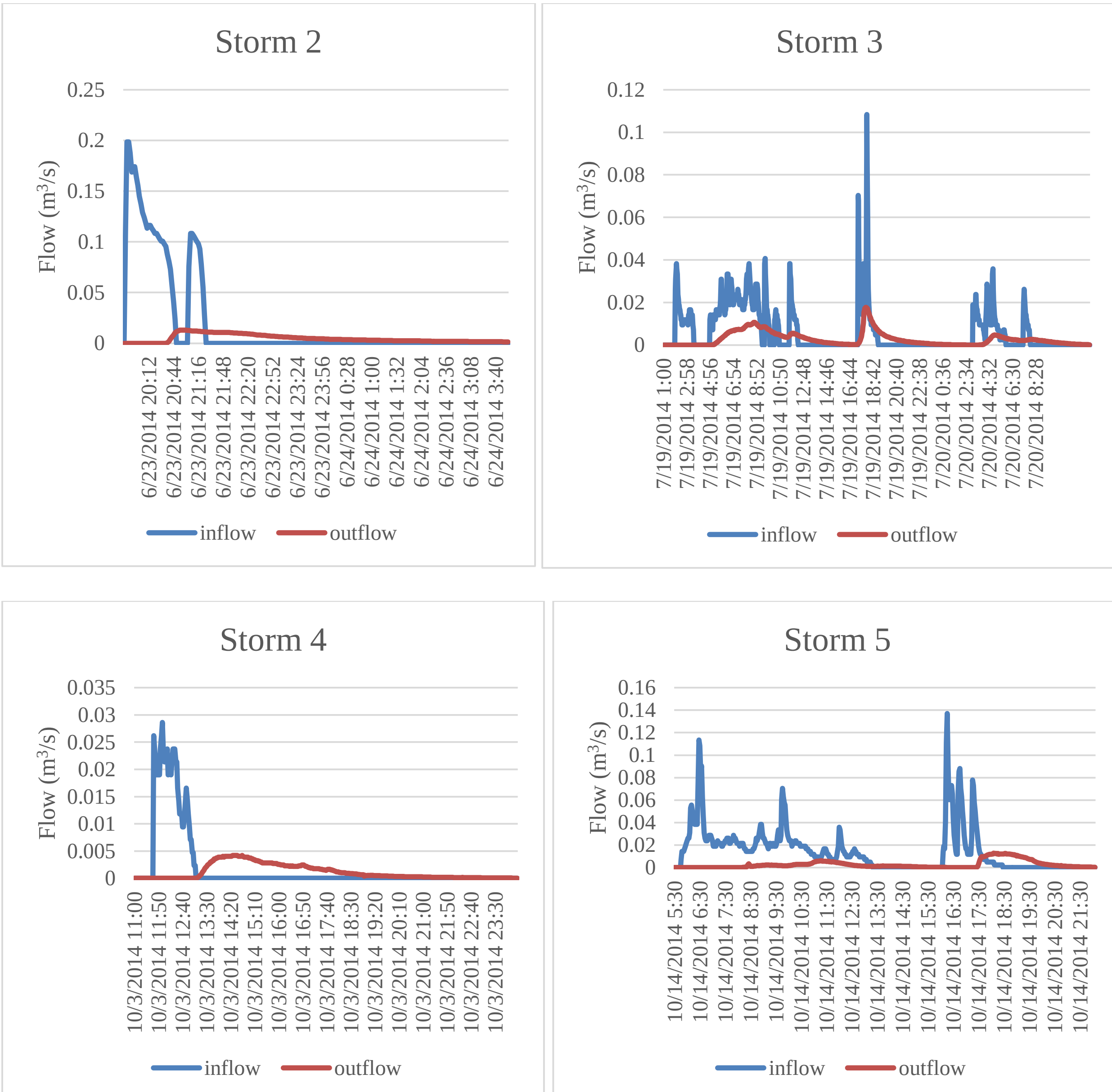

Figure 2.10. Sample hydrographs for Storms 2, 3, 4, and 5 showing reduced flows over entire storm durations

Both concentrations and loads for pollutants are presented here, but it is ultimately the loads that are most important to decrease since they represent the total amount of a pollutant entering a stream. Pollutant loads were calculated by multiplying the average concentration by the total volume of the storm.

The garden consistently reduced TSS. Reducing peak flows and providing a soil media barrier allowed sediment particles to settle out and remain in the body of the garden rather than flow out to Lily Branch. TSS concentrations were reduced on average by 22%, while TSS loads were reduced by 72%, with concentrations shown in Figure 2.11 and loads shown in Figure 2.12. TSS concentrations actually increased during Storm 8, which was a low volume storm with very little runoff. This small outflow volume compensated for increased concentration, resulting in a decreased load. Interestingly, many stormwater regulations require that stormwater management installations reduce TSS loads by an average of 80%, so this rain garden might not be considered a sufficient stormwater control for the parking deck in some jurisdictions.

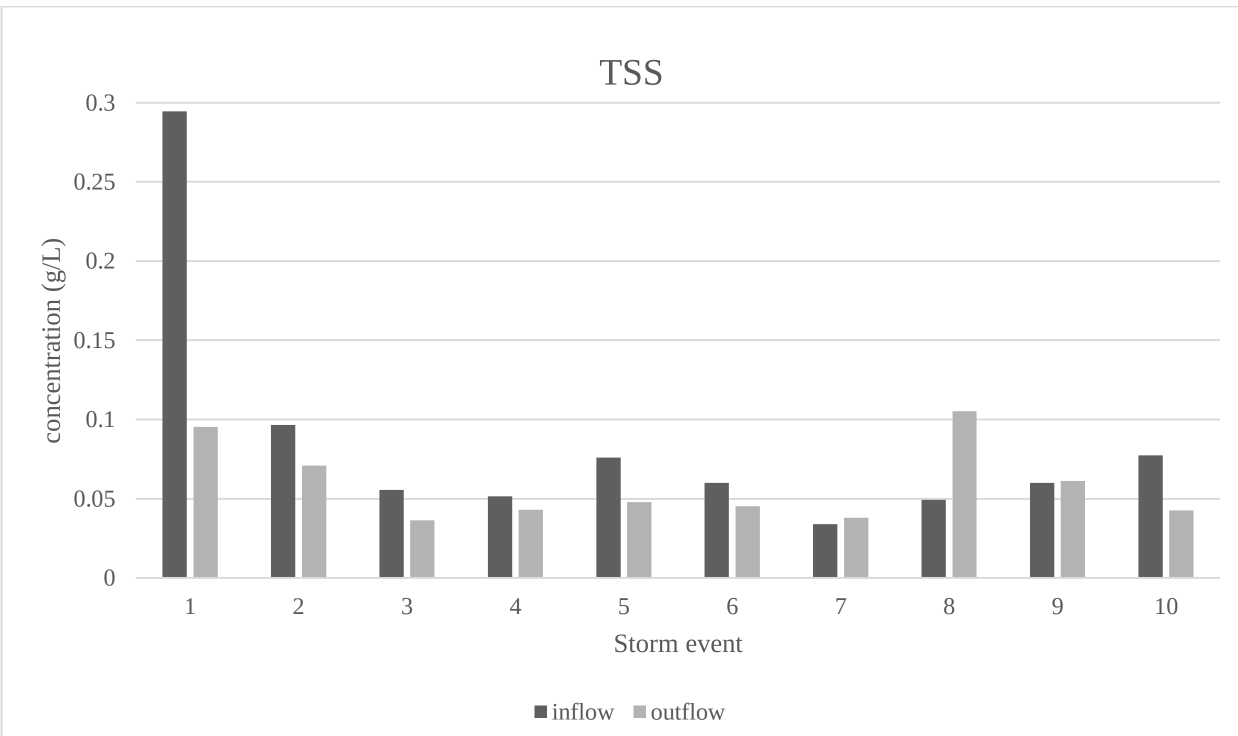

Figure 2.11. Individual TSS concentration measurements

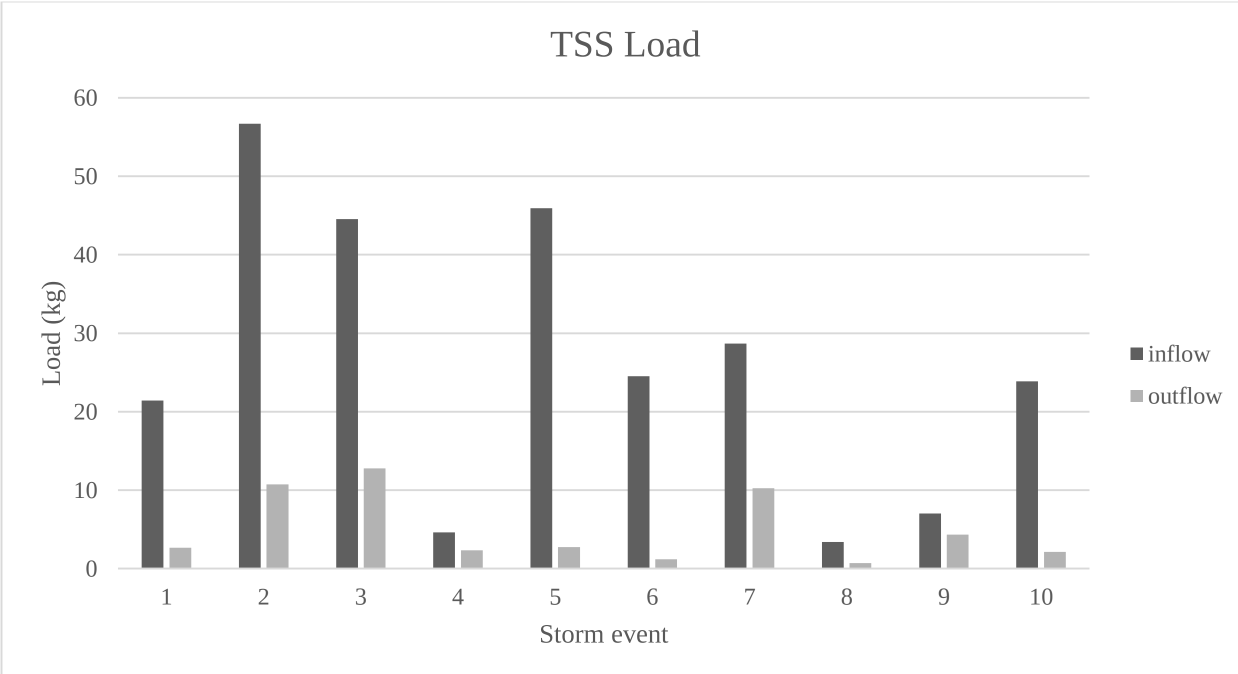

Figure 2.12. TSS loads

Somewhat alarmingly, the garden exported nitrate at an average of over 1,000% of inflow concentrations, shown in Figure 2.13. These numbers were slightly reduced when based on load because the outflow volume was reduced, with average outflow loads being increased 208%, shown in Figure 2.14. While it is possible that the high nitrate concentrations came from organic matter that was mixed into the soil media when the garden was originally installed, as mentioned in the previous chapter, it could also be a natural byproduct of the nitrification of ammonium, which has wide-ranging sources including runoff, soil, and the atmosphere.

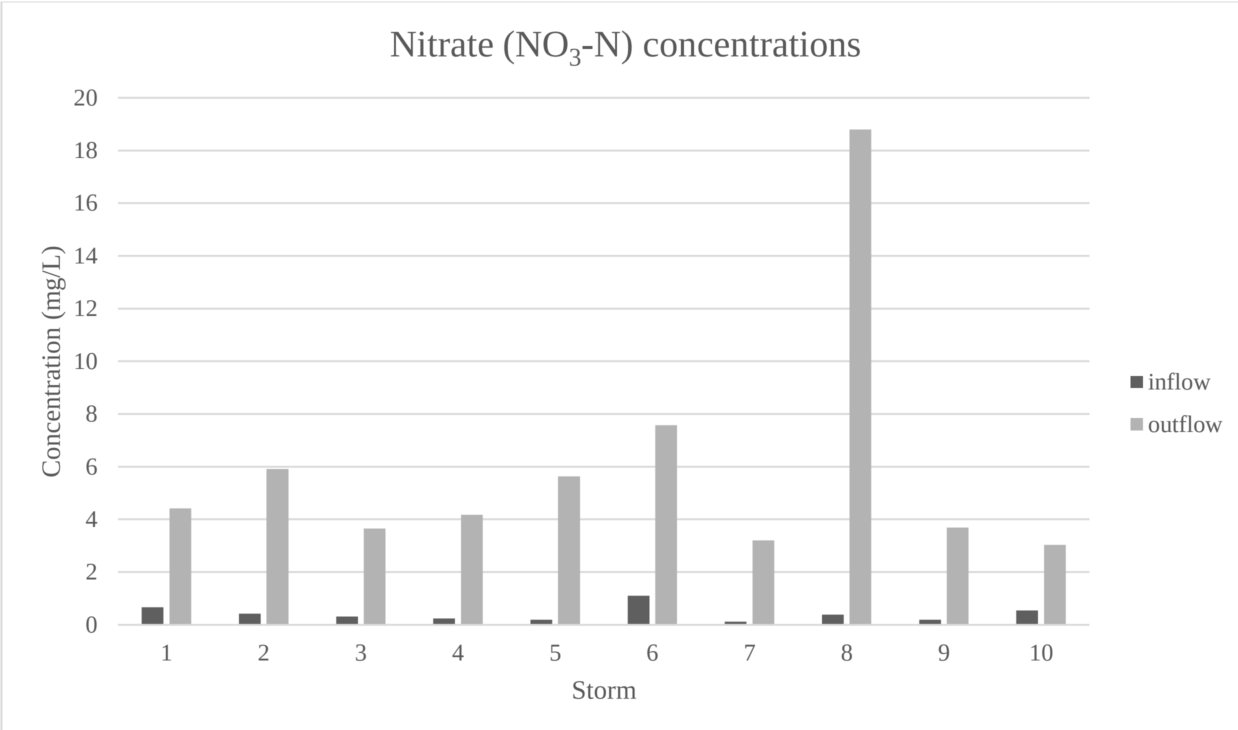

Figure 2.13. Individual nitrate concentrations

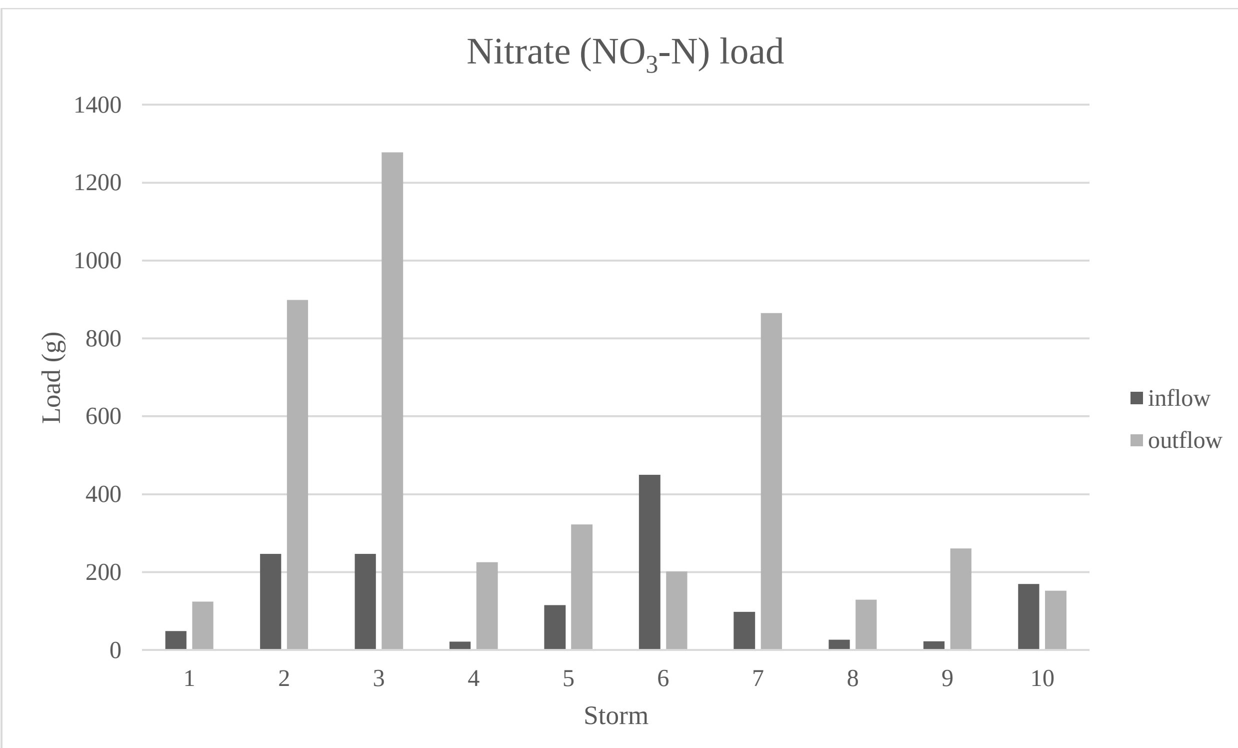

Figure 2.14. Individual nitrate loads

In fact, increased nitrate levels or poorly-reduced ones are a common result to many bioretention cells (Hunt et al. 2008, USEPA 2000, Kim et al. 2003). Nitrate is water-soluble, and unlike phosphorus and several other compounds, is not bound by sediment. Other than being swept out of the garden by water, it can be taken up by plants or denitrified by soil microbes into N_2 gas. Denitrification is often employed by creating a hypoxic environment that promotes anaerobic decomposition (Hunt et al. 2003, Kim et al. 2003, Stevenson & Cole 1999) and could be explored for this garden in the future. Such a fix could be accomplished by installing a so-called elbow pipe at the outflow to extend the residence time of runoff in the garden and give microbes more time to denitrify the water, shown in Figure 2.15. A simple retrofit version is an upturned PVC pipe that covers the outflow hole and requires a higher level of water to build up before it spills into the pipe and out into the stream.

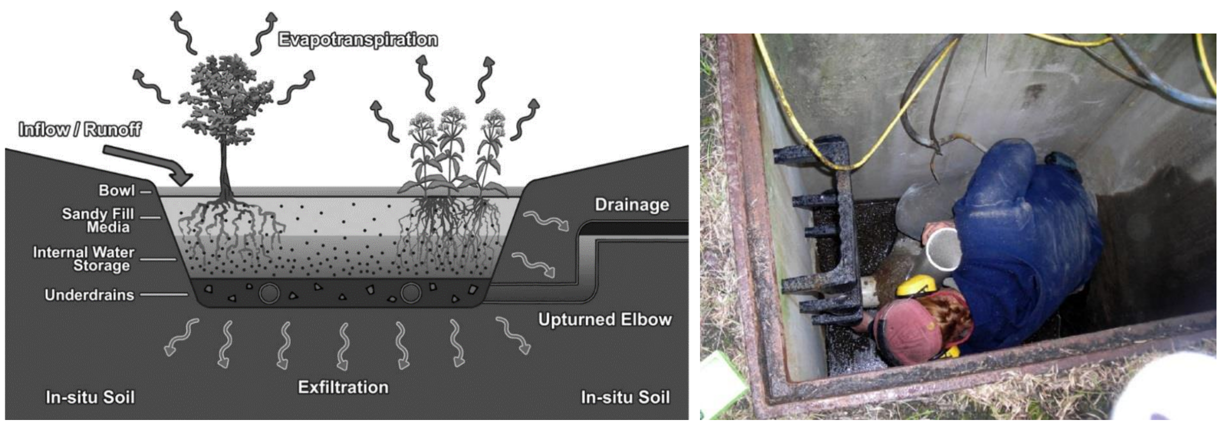

Figure 2.15. Elbow pipe modification schematic and retrofit in Rocky Mount, NC (Brown et al. 2009)

The rain garden had clear effects on the concentration and load of ammonium flowing in and out of it, shown in Figures 2.16 and 2.17. Concentrations were reduced on average by 82% and loads by 94%, and both were reduced in seven of the storms.

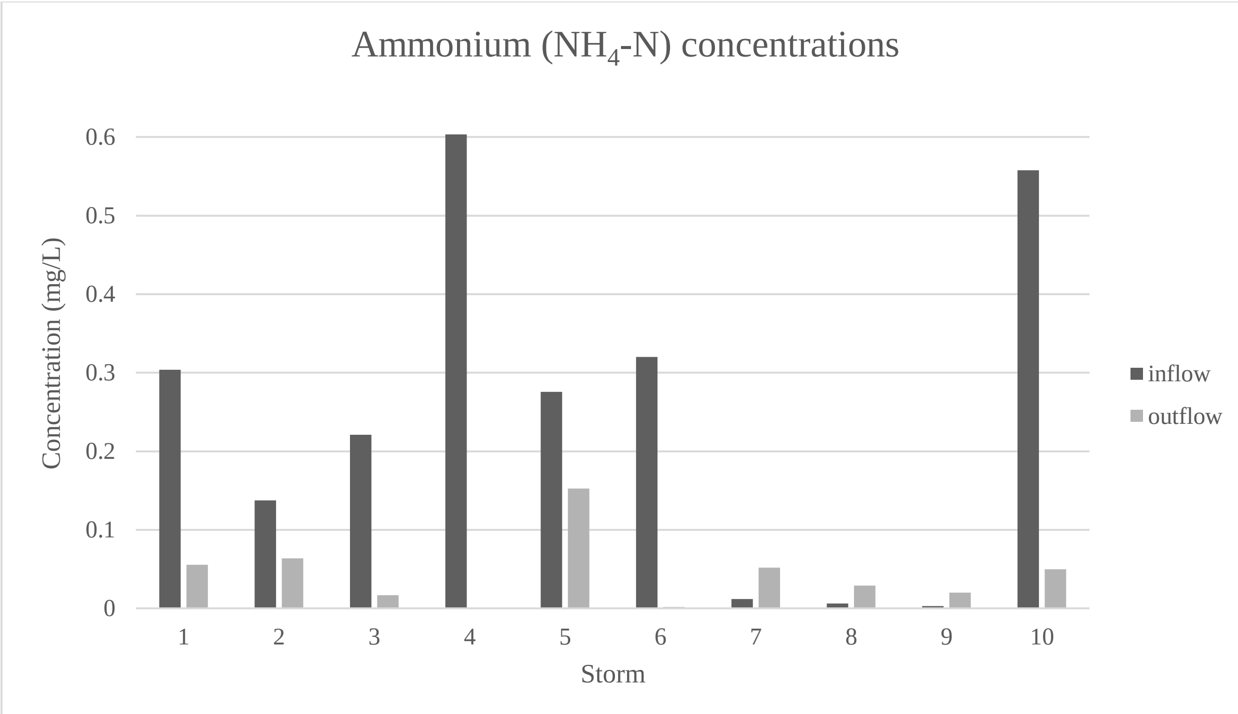

Figure 2.16. Ammonium concentrations

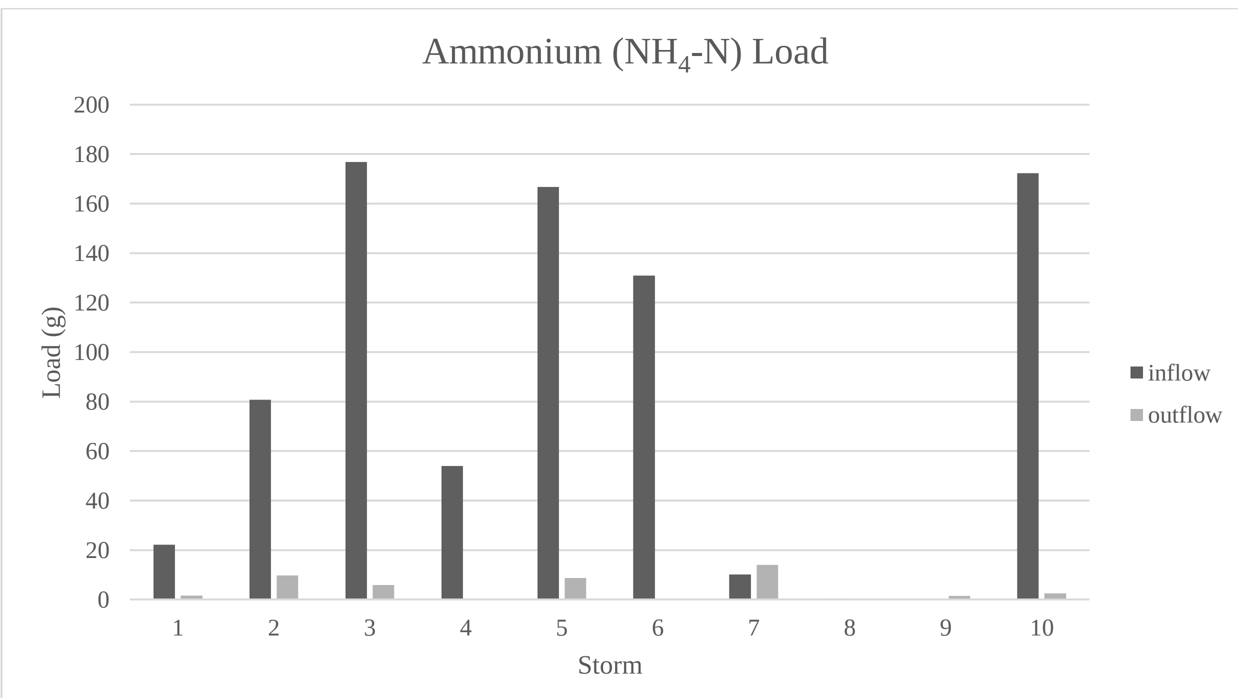

Figure 2.17. Ammonium loads

Total nitrogen concentration and loads are shown in Figures 2.18 and 2.19. Because total nitrogen incorporates nitrate, outflow concentrations were increased on average by 244%. However, when volume of runoff is taken into account to calculate load, only five of the storms showed an increase in load, and there was an overall average decrease of 25% across the storms. Nitrate and total nitrogen load notably decreased in Storms 6 and 10, due in part to their relatively high inflow and low outflow volumes.

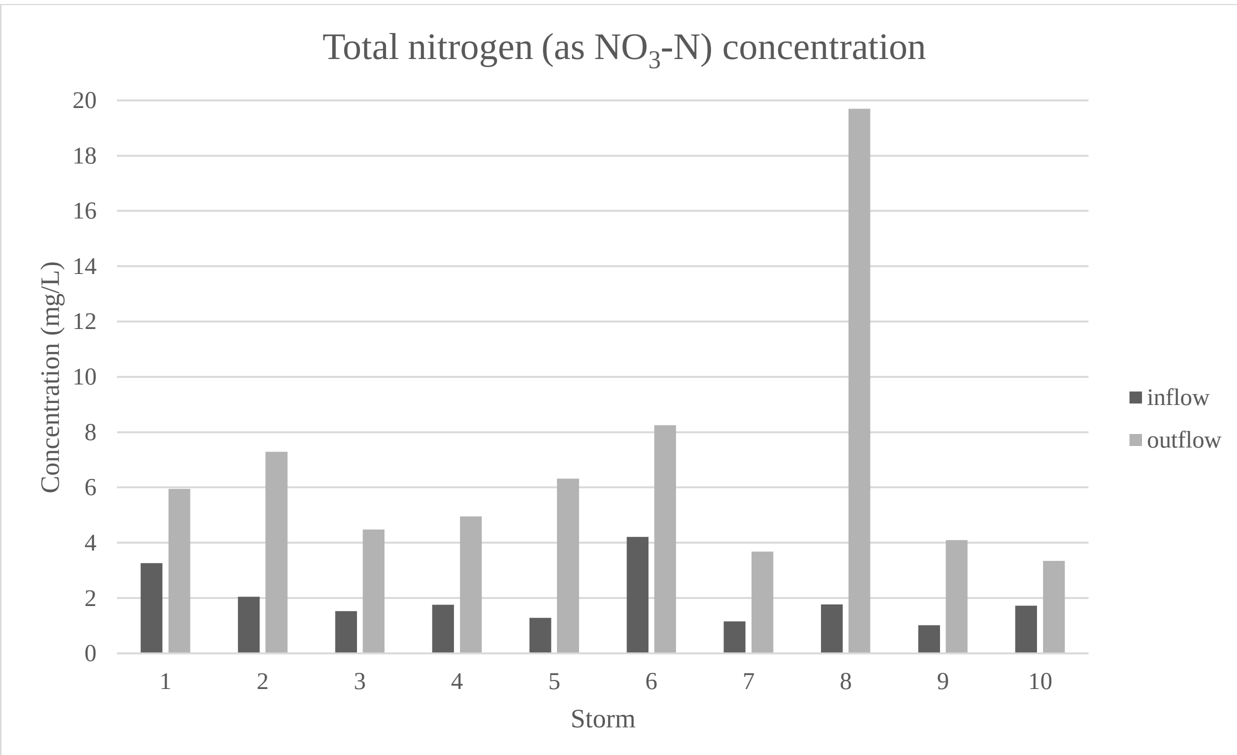

Figure 2.18. Total nitrogen concentrations

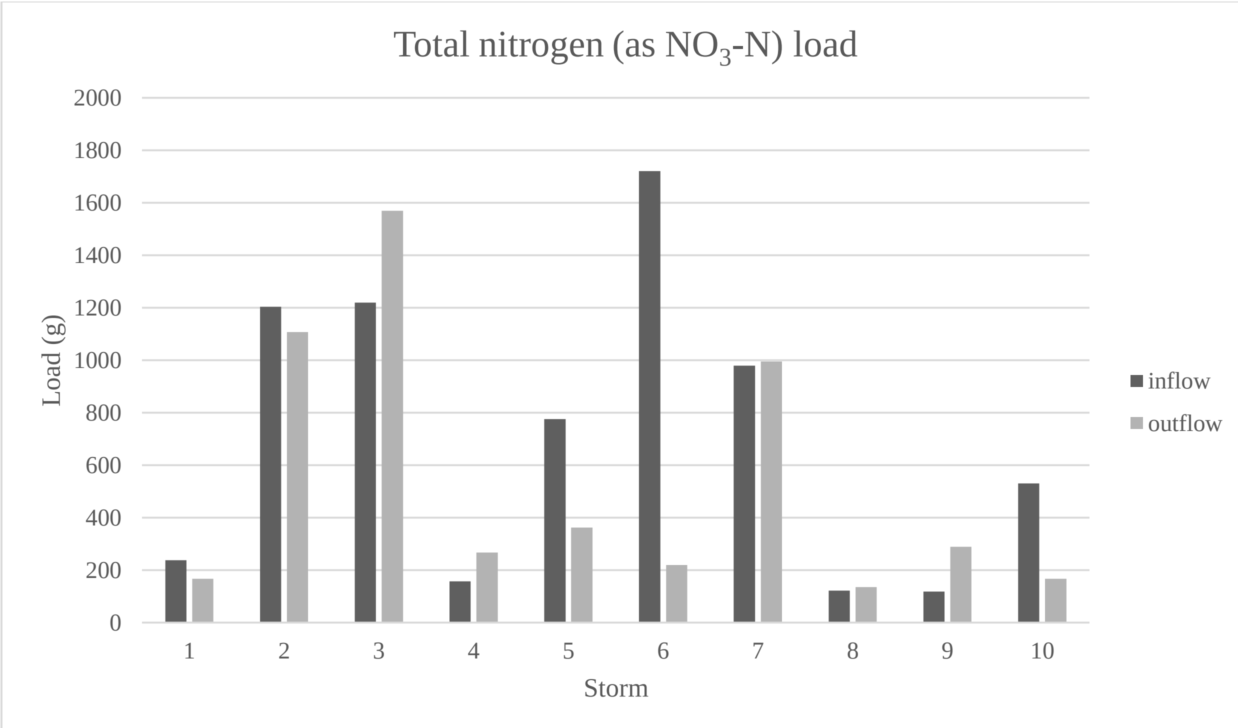

Figure 2.19. Total nitrogen loads

Soluble reactive phosphorus (SRP) was less consistent, shown in Figures 2.20 and 2.21. It exhibited a range of increases and decreases in concentration upon passing through the garden, possibly due to the presence of phosphorus in the soil media's organic matter. The overall average behavior across the 10 storms was a 54% increase in SRP concentration but a 33% decrease in SRP load. Load decreased across seven of the storms, with the remaining three loads corresponding to large increases in concentrations.

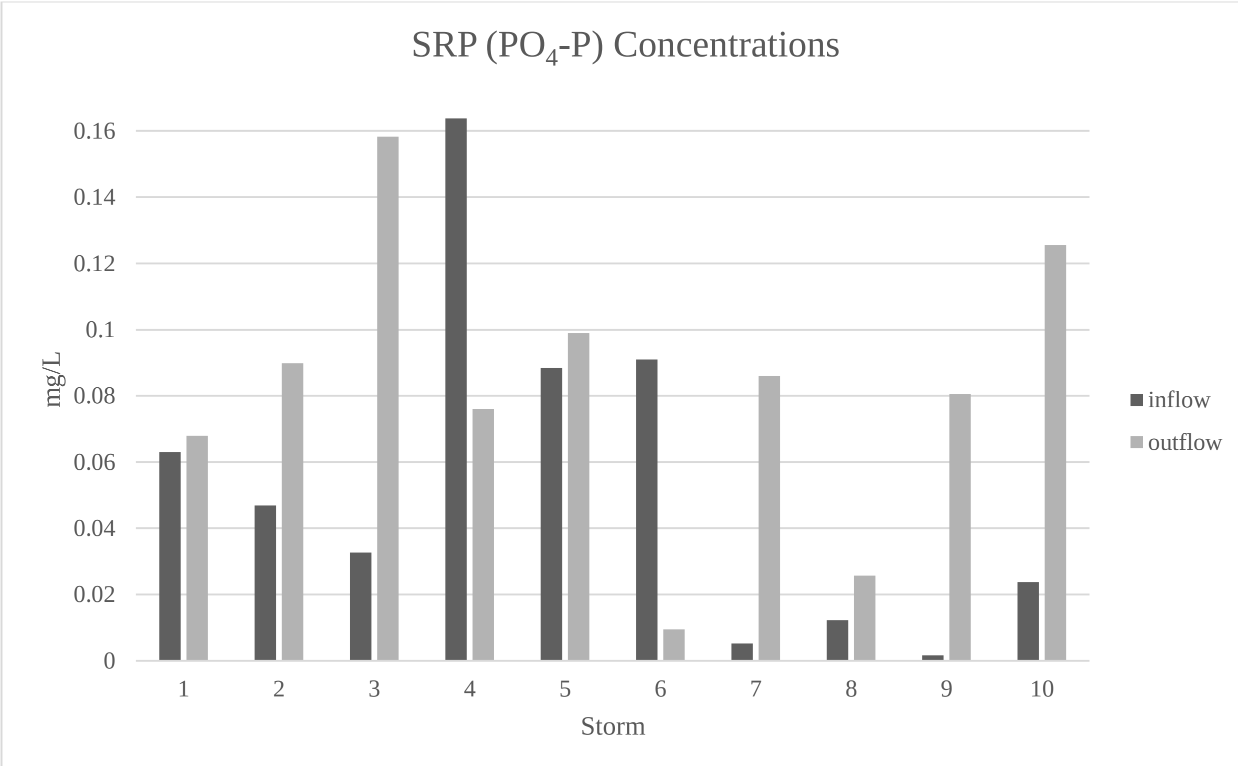

Figure 2.20. SRP concentrations

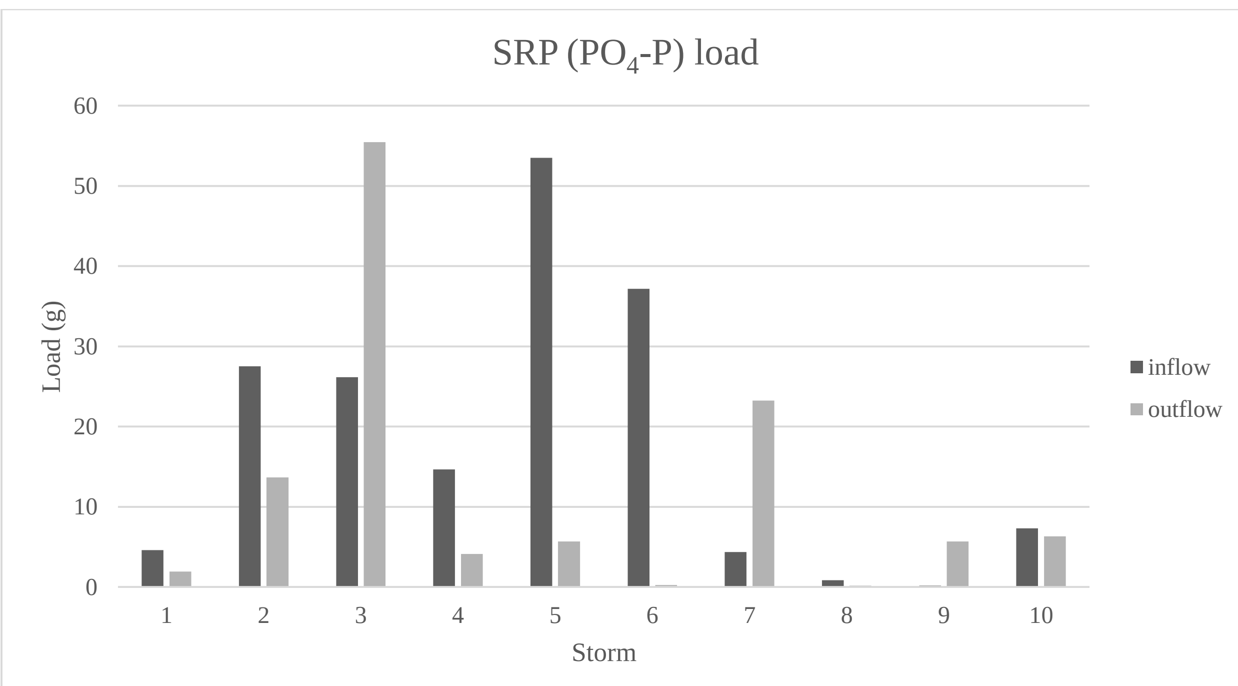

Figure 2.21. SRP loads

Total phosphorus also varied substantially, as shown in Figures 2.22 and 2.23. Despite the somewhat inconsistent behavior, overall concentrations averaged an 18% decrease over these 10 storms, and total phosphorus load was consistently decreased by an average of 68%. Likely phosphorus sources for this environment include fertilizers, fill organic matter, and phosphorus bound to eroding sediments; it is possible that the variation in phosphorus concentrations was due to activity by the UGA grounds crew in their regular maintenance activities near the rain garden, adding phosphorus to the garden that washed out during storm events.

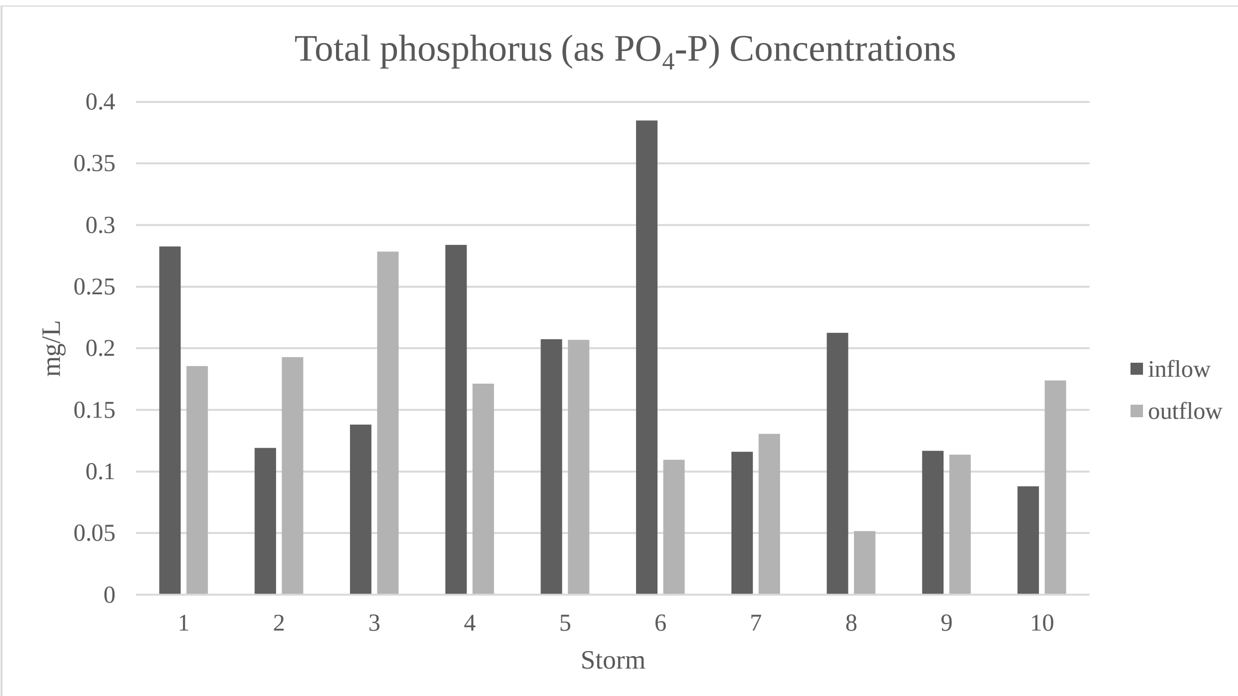

Figure 2.22. Total phosphorus concentrations

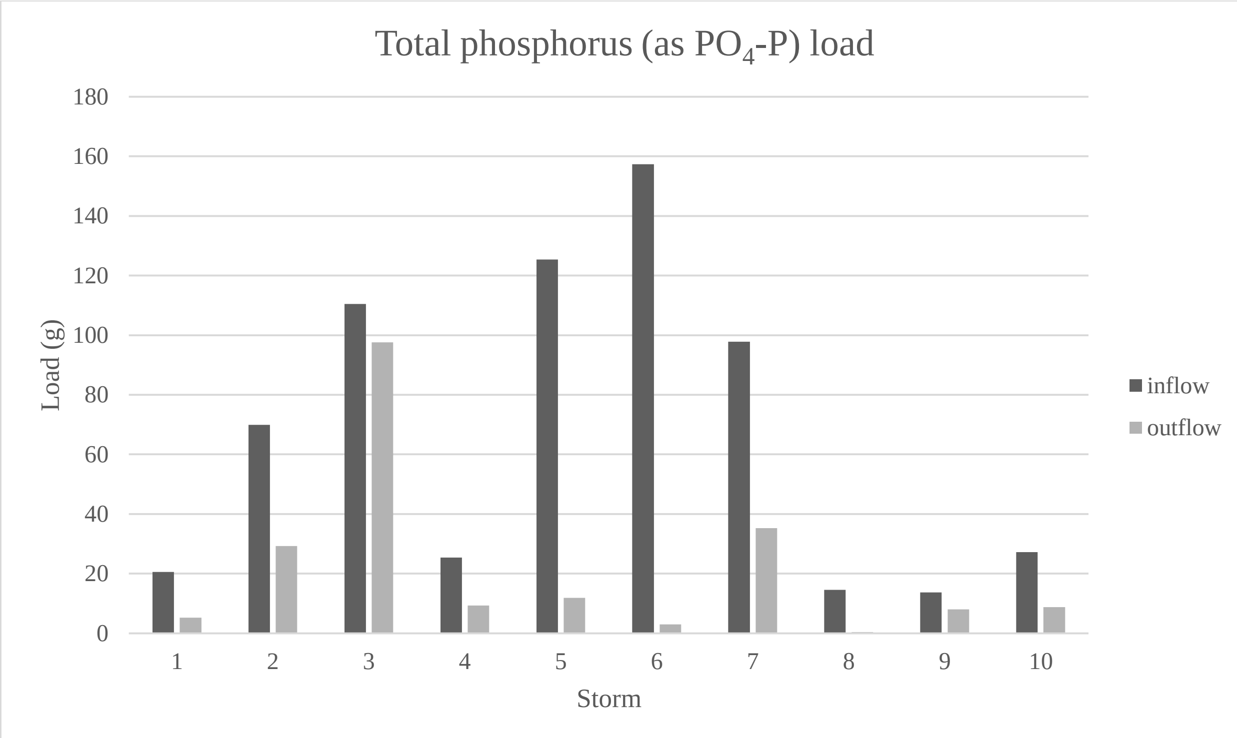

Figure 2.23. Total phosphorus loads

Individual TSS samples across four different storms are shown in Figure 2.24. These samples represent four hours of inflow data and 12 hours of outflow data, with the exception of Storm 1 which only had 14 inflow samples. TSS values mirrored individual flow patterns, with high first-flush concentrations at the inflow quickly decreasing to a steady, low value; and low, steady values at the outflow. Inflow TSS values were high during only the first hour of the storm event. Individual nitrate samples for two storms are shown in Figure 2.25. Nitrate inflow values were low and consistent over the entire set of samples, while the outflow values exhibited high first-flush concentrations that gradually decreased over the next two to three hours.

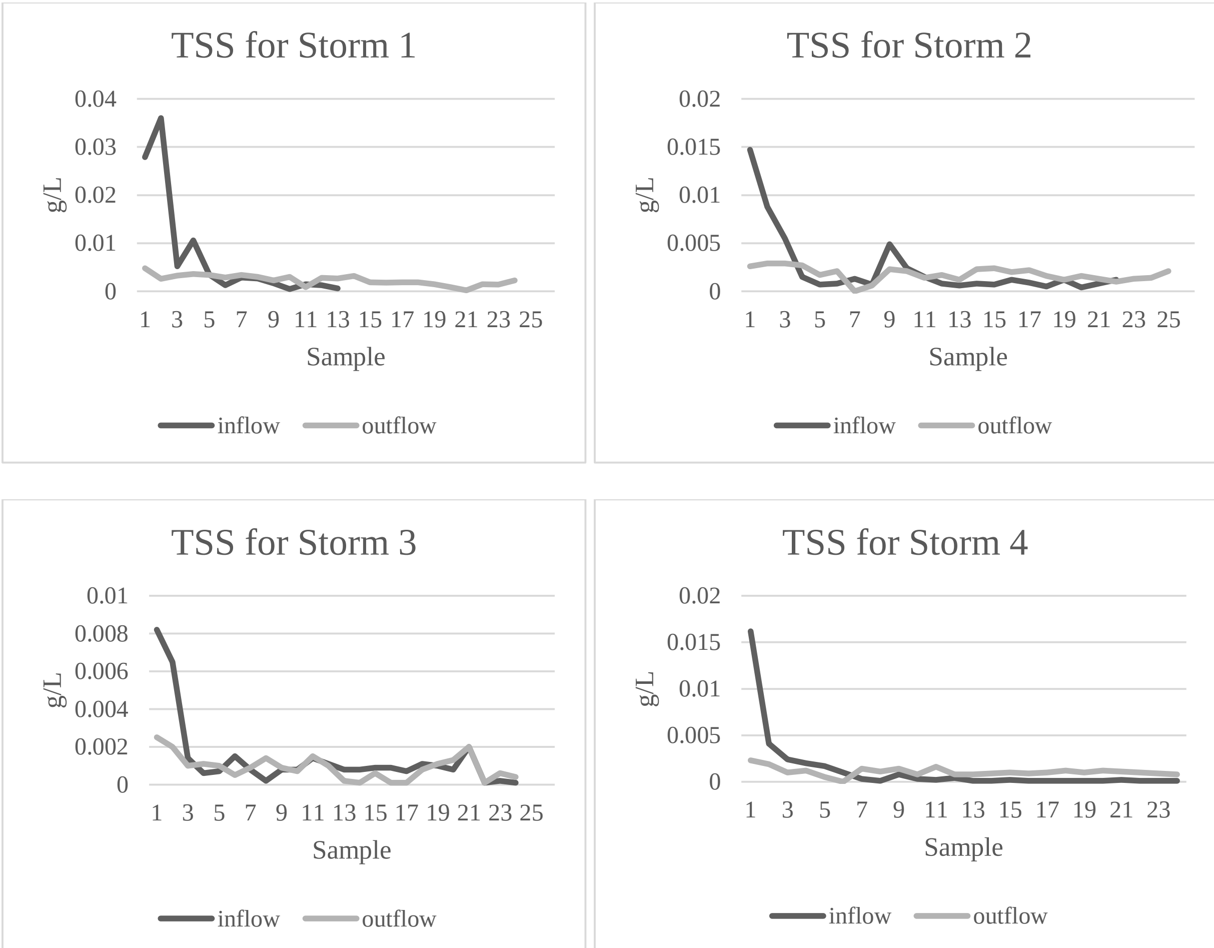

Figure 2.24. Individual TSS measurements for four storms

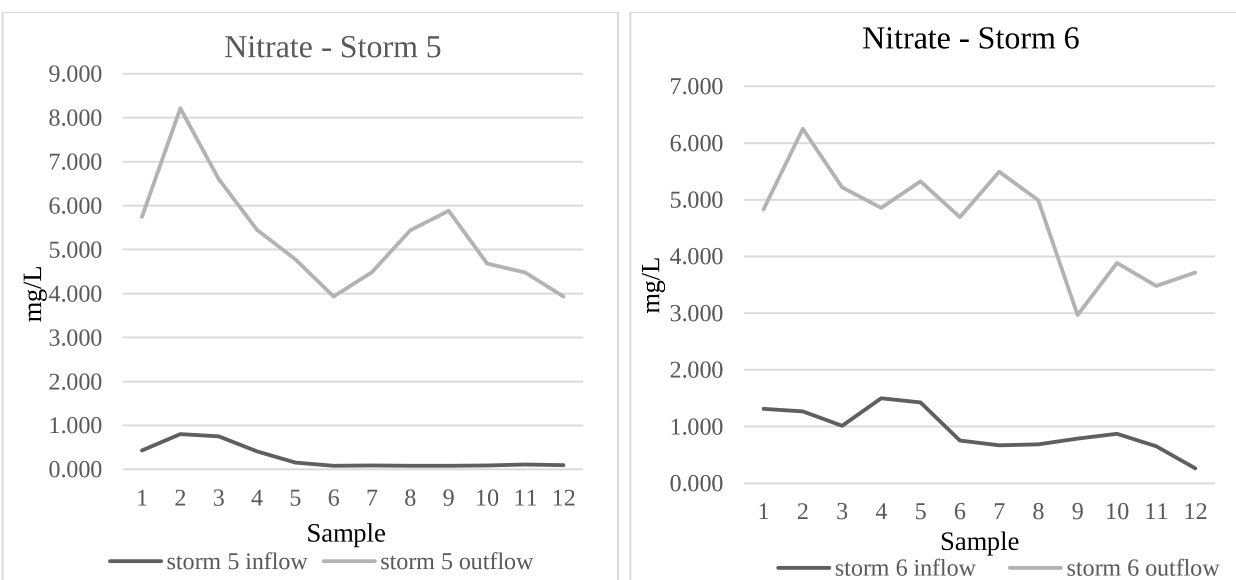

Figure 2.25. Individual nitrate measurements for two storms

Soil monitoring results

Ksat measurements taken across the garden present evidence of non-uniformity within the soil. Ksat values near the inflow of the garden tended to be lower than in the middle or outflow portions of the garden. For all sites, Ksat was highest at around 0.77 m depth and decreased substantially at 1.01 m, potentially due to surrounding clay material that formed a barrier to water movement.

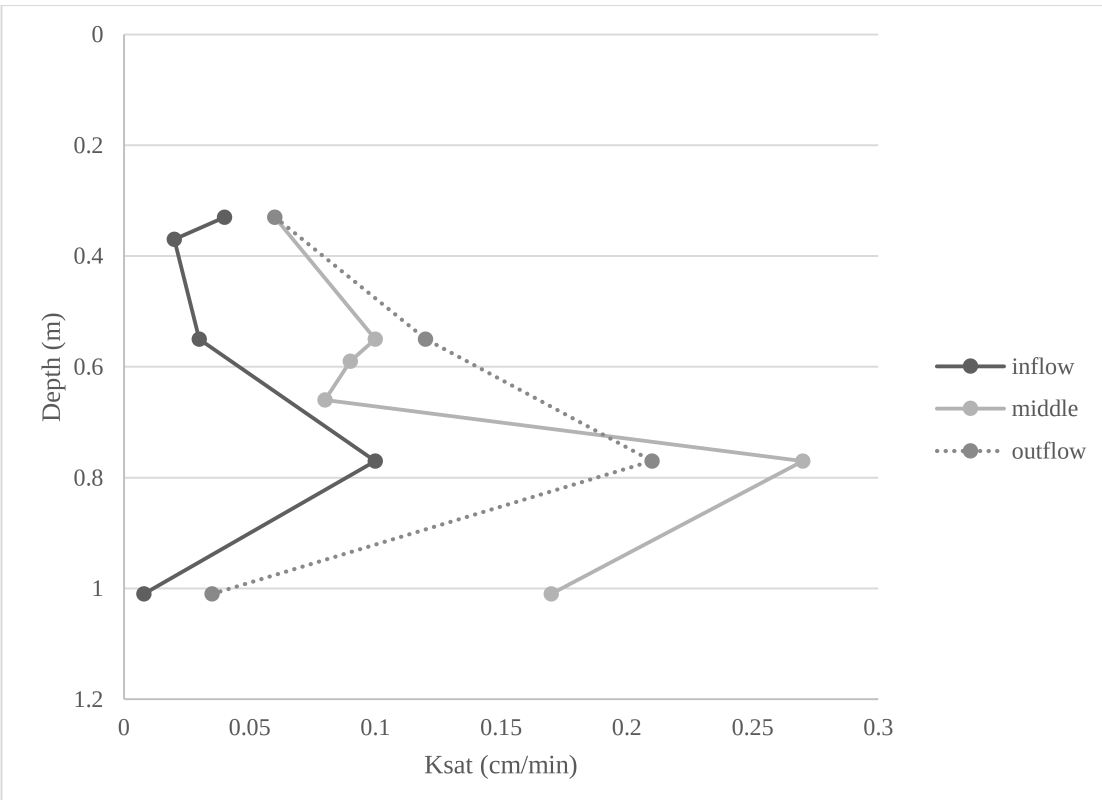

Figure 2.26. Ksat measurements at different locations and depths

One possibility accounting for these differences is that the fill at the inflow of the garden is becoming clogged with inflowing sediment because it receives water from every storm event, whereas the middle and outflow of the garden do not always receive runoff. If the soil were uniform at the initial installation of the garden, then substantial differences in the Ksat value across the garden would suggest that sedimentation could be occurring and altering the behavior of the garden in a non-uniform fashion. However, conclusions about the state of the garden based on these Ksat measurements should not be drawn without statistically rigorous replicates. Thus, whether or not the soil was entirely uniform to begin with is a question not addressed by this thesis, but Kathryn Shepard found concentrations of zinc non-uniformly distributed throughout the garden, suggesting soil non-uniformity (2013).

Soil moisture readings were collected by the Em50 dataloggers for the Decagon devices once every 15 minutes. Each logger's readings give insight into which parts of the soil receive water and when. Figure 2.27 shows graphs of the readings associated with Storm 5 in October 2014.

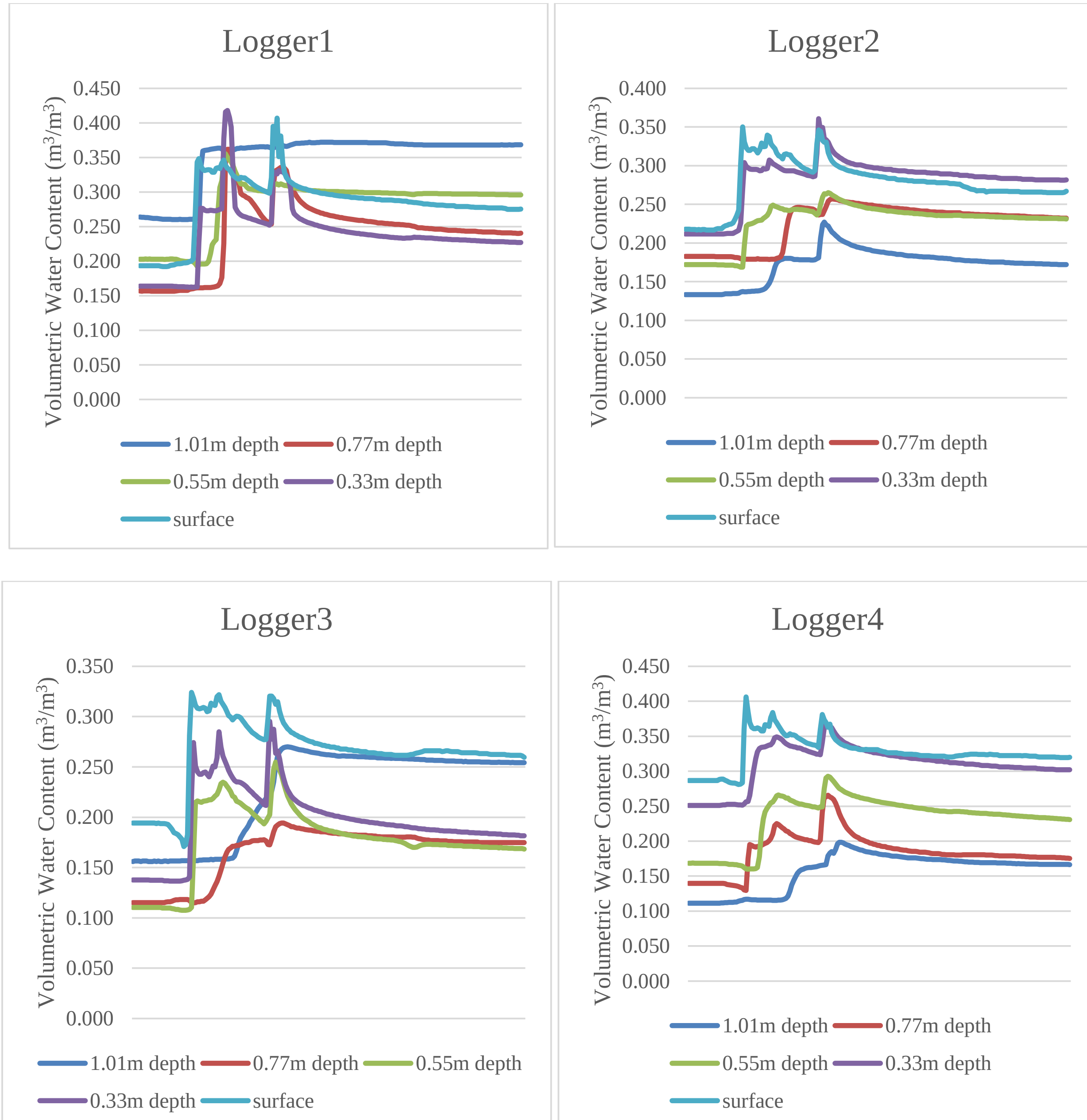

Figure 2.27. Soil moisture sensor data (volumetric water content) from Storm 5, over a 50-hour period starting October 14, 2014, at midnight

Logger 1 is located at the inflow side of the garden. Its graph shows that the surface sensor was the first to react to the presence of runoff, as expected, but then the deepest sensor at 1.01 m logged an increase in volumetric water content (VWC) next, contrary to expectations. This discrepancy points to a preferential flow path, possibly introduced by the installation of the moisture sensor though care was taken to avoid such a scenario as much as possible. Following the reaction of the deepest buried sensor, the sensors at 0.33 m, 0.55 m, and 0.77 m saw an increase in moisture content, as expected. The sensor at the lowest depth also had the highest moisture content, both before and after the storm, showing that this layer retained water and was unaffected by evapotranspiration effects. It was followed in moisture content by the 0.55 m layer, the surface, 0.77 m, and 0.33 m, possibly due to roots of plants or irregularities in soil composition.

Logger 2 is located in the middle of the rain garden. Its layers received water and had increased moisture content in the order expected, that is, from the surface downward. Higher layers had higher moisture content due to less water reaching subsequent layers. The layers were grouped with regards to their moisture content, with the surface and 0.33 m, and 0.55 m and 0.77 m layers maintaining similar moisture content both before and after the storm. The deepest layer had the lowest moisture content at all times.

Logger 3 was located farthest from the inflow at the opposite end of the garden. Its layers reacted in the expected order to seeing water arrive, but the deepest sensor unexpectedly had the second highest moisture content at all times, with moisture levels close to those at the surface; similar to the inflow Logger 1, this deepest layer is effectively holding onto moisture it receives from higher levels.

Logger 4 is also located in the middle of the garden, in line with Logger 2, but aligned along the side of the garden. Sensors generally exhibited increasing water content in the order expected, with the exception of the sensor at 0.77 m that started measuring increased moisture content slightly before the sensor at 0.55 m. As with Logger 2, sensors located at lower depths measured less water content as less water reached the middle layers.

The inflow and outflow moisture sensors logged different behavior at the lowest depths of the rain garden than did the sensors in the middle of the garden. However, this discrepancy is in line with the measured Ksat values listed earlier; the inflow and outflow 1.01 m depths had small Ksat values, meaning that water does not flow through that part of the soil easily when the soil is saturated. Thus, small Ksat values could equate to high VWC, as those layers receive water and then do a poor job at releasing the water. It is possible that the standpipe near the outflow and that the perforated pipe tile drain system create some complicating effects near the loggers in addition to non-uniform soil media. While the locations of the perforated pipes is approximately known from original drawing plans, the exact final locations were not documented on the surface of the garden except for the presence of several observation wells.

Conclusion

The Lily Branch rain garden is a fairly effective LID installation on the UGA campus. It reduced peak flows of runoff from a nearby parking deck on the East Village campus, gradually releasing water to the nearby stream Lily Branch. The rain garden consistently decreased the loads of TSS, total ammonium, and total phosphorus that flowed from the parking lot into Lily Branch, but it increased nitrate loads. Measures should be taken to reduce the nitrate flowing out of the rain garden, such as the installation of an elbow pipe over the outflow opening. Additional rain gardens on the UGA campus of similar size and design may be having similar nitrate export issues. Ideally, all rain gardens on campus would be monitored continuously with automated samplers, but the necessary man-power and budget for those installations make such an endeavor unrealistic. Monitoring a subset of campus rain gardens, such as all rain gardens larger than 100 m^2, is tractable and should be done. If nitrate export is common to all of the larger rain gardens, which treat larger volumes of water, then future rain garden installations should use a different design that promotes denitrification.

The soil's saturated hydraulic conductivity (Ksat) was not uniform across the garden, pointing to the possibility that sedimentation is occurring at the garden's inflow. This situation should be monitored further to see how sedimentation is impacting the garden's ability to mitigate runoff and if maintenance measures are required to keep it functioning properly. Moisture sensors revealed further heterogeneity across the garden, with the inflow and outflow ends of the garden appearing to retain water in the deepest sections of the garden. Overall, this rain garden is effectively mitigating runoff, and adjustments such as the installation of an elbow pipe fixture will make it more effective in the future.

CHAPTER 3

WATERSHED-SCALE MODELING OF RAIN GARDENS

The effectiveness of individual rain gardens at reducing runoff volume, peak discharge, and pollutants that pass through them is well-documented, as discussed in the previous chapters of this thesis. However, since the ultimate motivation for using LID is to improve the health of streams, it makes sense to examine the collective impacts of rain gardens on stream flow and nutrient content. This chapter discusses the impacts of rain gardens at the watershed-scale, focusing on their effects on discharge at a watershed's outlet. One question to consider is what percentage of a watershed's runoff must be treated by rain gardens in order to see noticeable reductions in peak flow downstream. I attempted to answer this question using the Soil & Water Assessment Tool (SWAT) to simulate discharge in the Lily Branch watershed.

SWAT was developed by the USDA and is a free, semi-distributed, physical-based modeling tool that simulates physical processes in the soil and streams based on input data. Input required for a SWAT simulation includes a digital elevation model (DEM), land use, and soil data, as well as weather information including precipitation, temperature, relative humidity, solar radiation, and wind data. Using the DEM to calculate gradients, SWAT delineates a watershed and then uses the remaining data to calculate various hydrological parameters over a specified set of years, estimating flow, sedimentation, and nutrient movement through a watershed. SWAT also provides modules for simulating urban stormwater best management practices (BMPs).

Methods

Data for the Lily Branch watershed were downloaded from a number of sources, listed in Table 3.1.

Table 3.1. Data used for Lily Branch watershed delineating and simulation

Data type	**Source**
DEM	NRCS USDA Data Gateway (10m)
Soil	US SSURGO soils database (10m)
Land use	National Land Cover Dataset (NLCD) 2006 (30m)
Weather	TAMU Global Weather Data (12/1/2001 - 12/31-2010)

Using the DEM and a SWAT-recommended critical source area of 3.79 hectares, I used SWAT to delineate the Lily Branch watershed, which is approximately 397 acres in size and shown in Figure 3.1. The land use, shown in Figure 3.2, is primarily urban, with the uses listed in Table 3.2. A large portion of this land is UGA property that contains the Foley baseball stadium and largely-impervious East Village portion of campus; Lily Branch flows to campus from the residential Five Points area, passing behind houses, apartment complexes, and an elementary school.

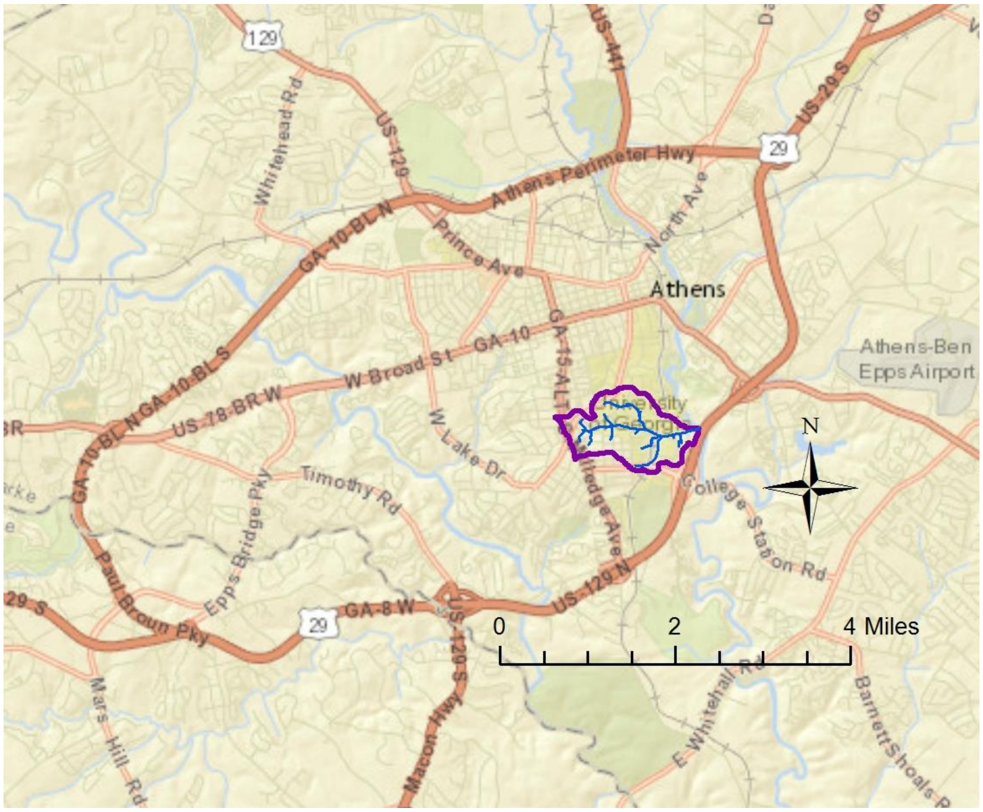

Figure 3.1. Delineated Lily Branch watershed in Athens, outlined in purple

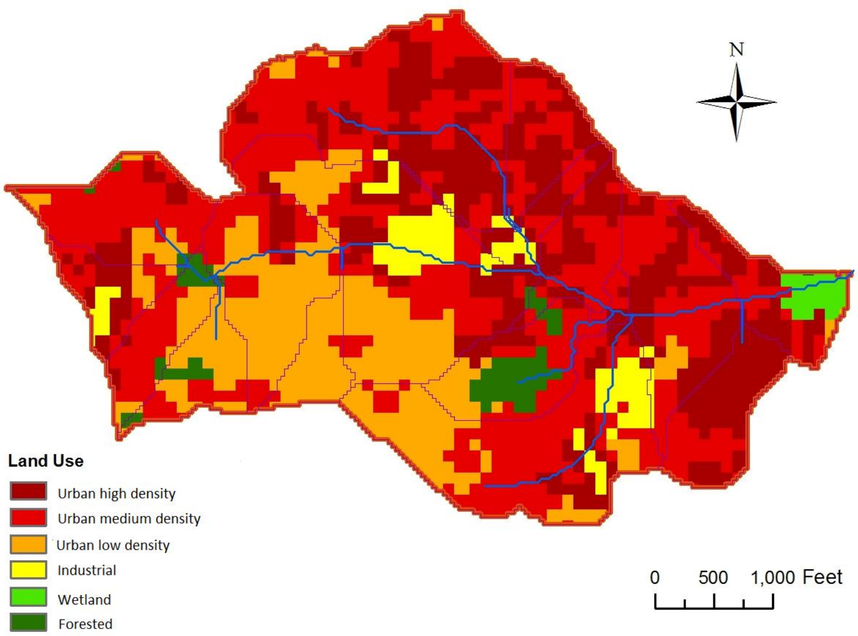

Figure 3.2. Land use in delineated Lily Branch watershed

Table 3.2. Land use in Lily Branch watershed

Land use type	**Percent of watershed**
Urban high density	27.31
Urban medium density	42.06
Urban low density	21.29
Industrial	4.99
Deciduous forest	3.12
Forested wetland	1.22

To simulate hydrology, I used SWAT to split the watershed into subbasins based on channel outlets and tributaries, and broke those subbasins into smaller, homogeneous units called Hydrologic Response Units (HRUs) based on similar land use, underlying soils, and slope. The SWAT simulation for the watershed consisted of daily-timestep runs between the dates of 12/01/2001 and 12/31/2010, with an initial 2 year warm-up period. The daily Green & Ampt (G&A) routing method was used, as it bases its runoff calculations on soil infiltration. Two advantages of G&A over the Curve Number method (CN) are that G&A takes into account timing and intensity of storms and also underlying soil data. CN bases its calculations on total precipitation volume and is empirically-based, estimating runoff generation based on land use. Green & Ampt is thus likely to give more accurate estimates based on the specific physical parameters of the Lily Branch watershed.

The results of the baseline simulation showed “flashy” behavior in this urbanized watershed, with large peak flows occurring quickly after precipitation events and then rapidly dissipating. The baseline hydrograph is shown in Figure 3.3. These large peaks above the base flow are presumably due to the largely impervious nature of the surrounding watershed, and it is these peaks that rain gardens and bioretention techniques are used to control.

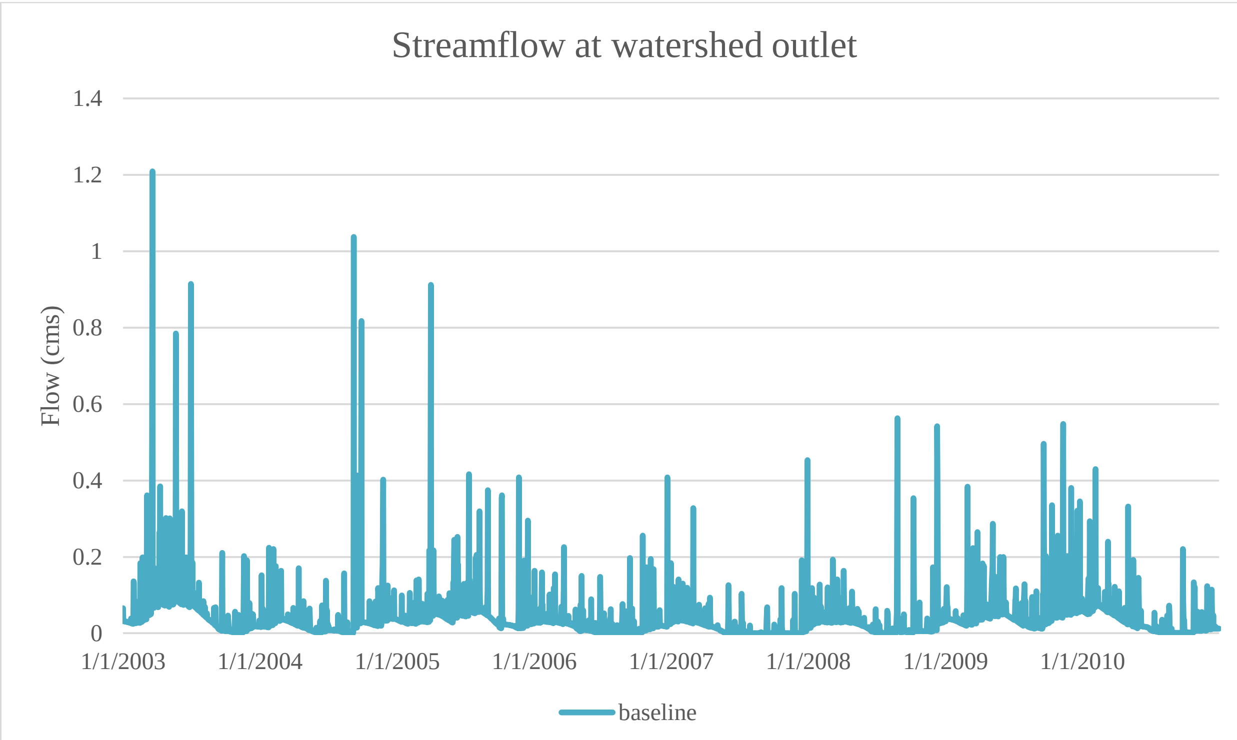

Figure 3.3. Baseline simulation

Modeling rain gardens

SWAT provides a module for simulating stormwater Best Management Practices, though there is currently no “rain garden” or bioretention setting in this module, so rain gardens must be approximated. A new rain garden option is currently being added to SWAT and will likely be available within the next few years (Her & Jeong 2015). To include rain gardens in these simulations, I activated the wetland module within SWAT and modeled rain gardens as wetlands with a hydraulically-conductive (leaky) bottom, with hydraulic conductivity set to the maximum value. Wetlands are modeled in a distributed fashion in SWAT, so no spatially-explicit rain gardens can be specified in this style of modeling. Runoff is generated for each HRU based on the given land use data, and then a user-specified portion of runoff is sent through the theoretical rain gardens to determine reductions in discharge.

Using this distributed method, I simulated the effects of various amounts of runoff in a watershed being directed through rain gardens, starting at 0% and generally increasing by 10% with each simulation. Presented here are the results from the following scenarios to demonstrate different levels of rain garden coverage in a watershed: 0%, 1%, 10%, 30%, 50%, 90%, and 100%.

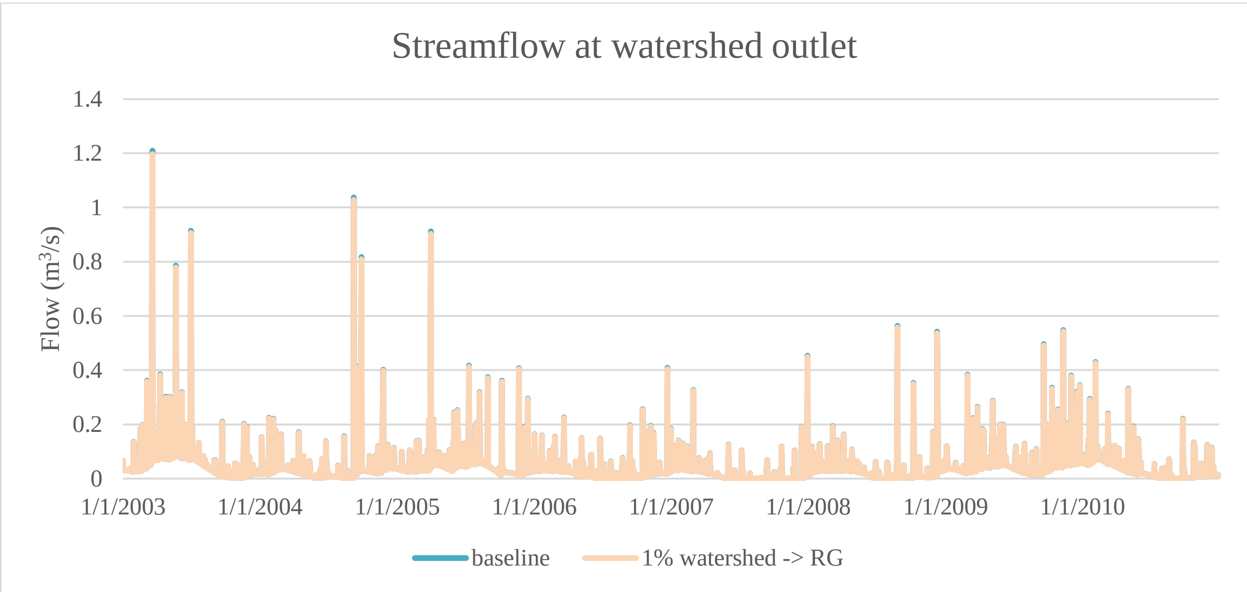

Figure 3.4. Simulation of 1% of a watershed's runoff treated by rain gardens

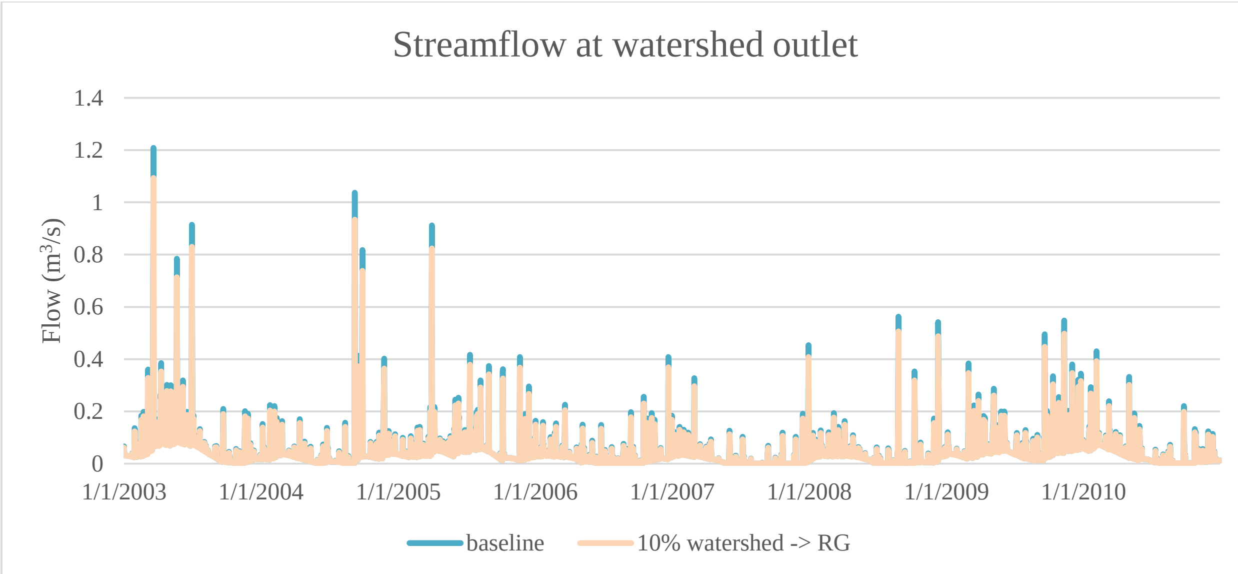

Figure 3.5. Simulation of 10% of a watershed's runoff treated by rain gardens

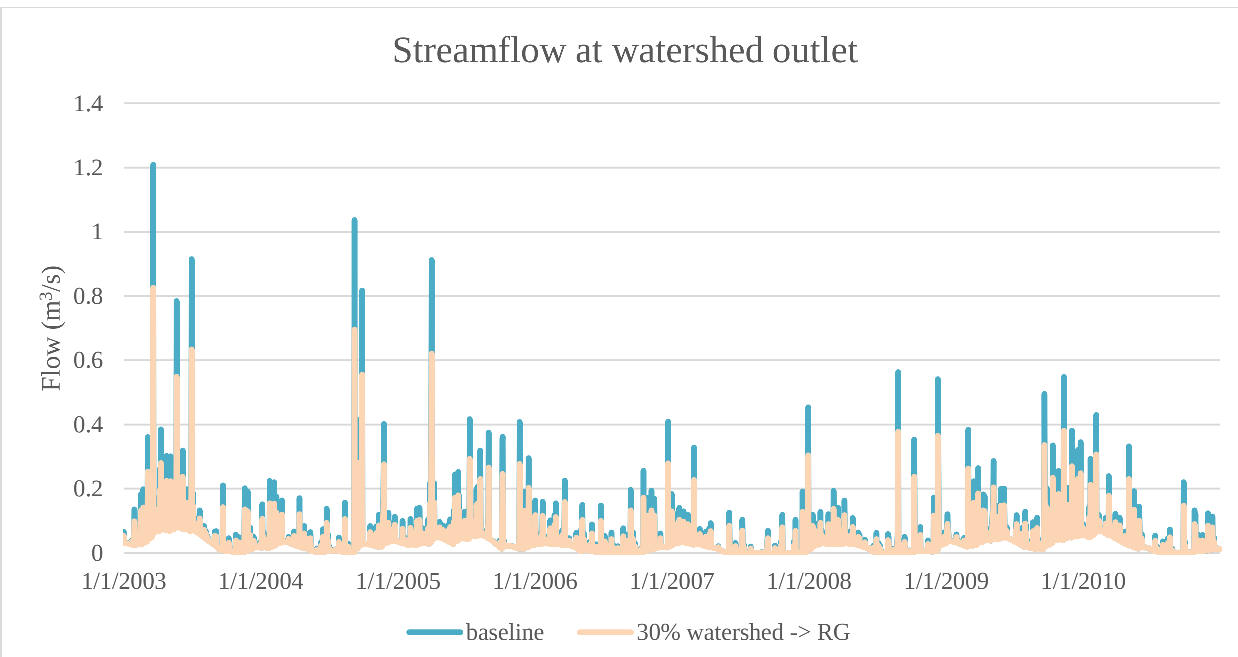

Figure 3.6. Simulation of 30% of a watershed's runoff treated by rain gardens

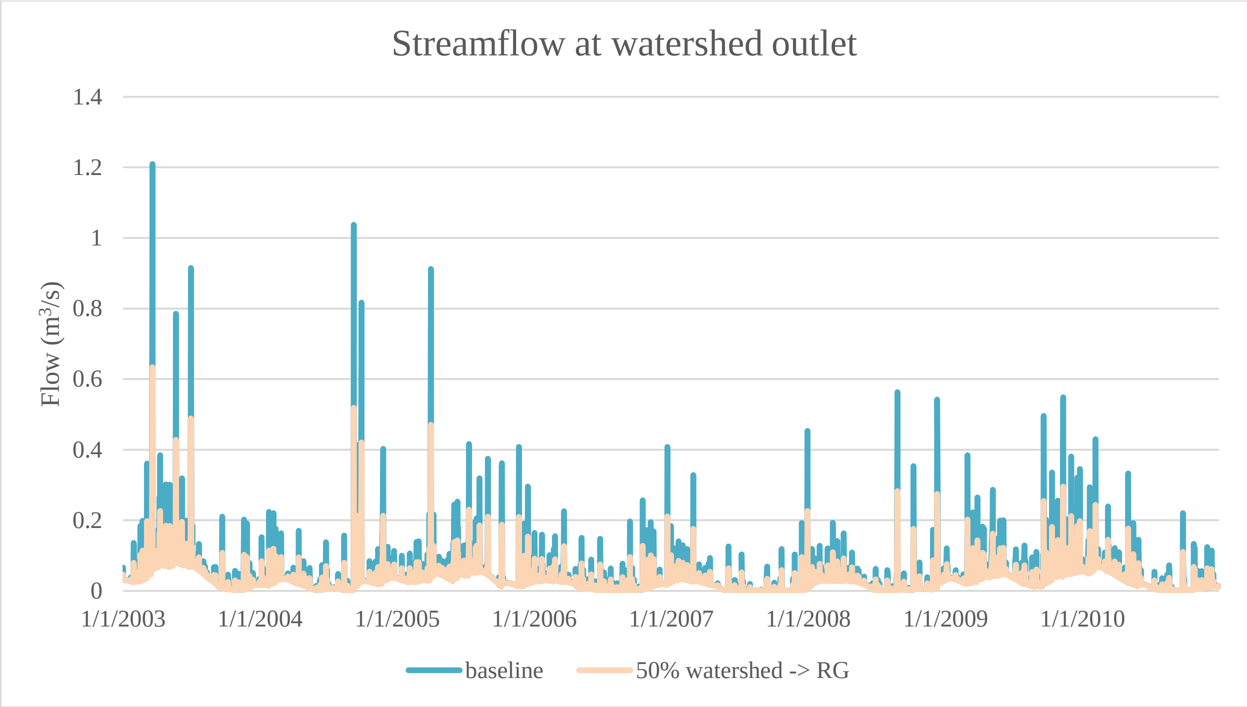

Figure 3.7. Simulation of 50% of a watershed's runoff treated by rain gardens

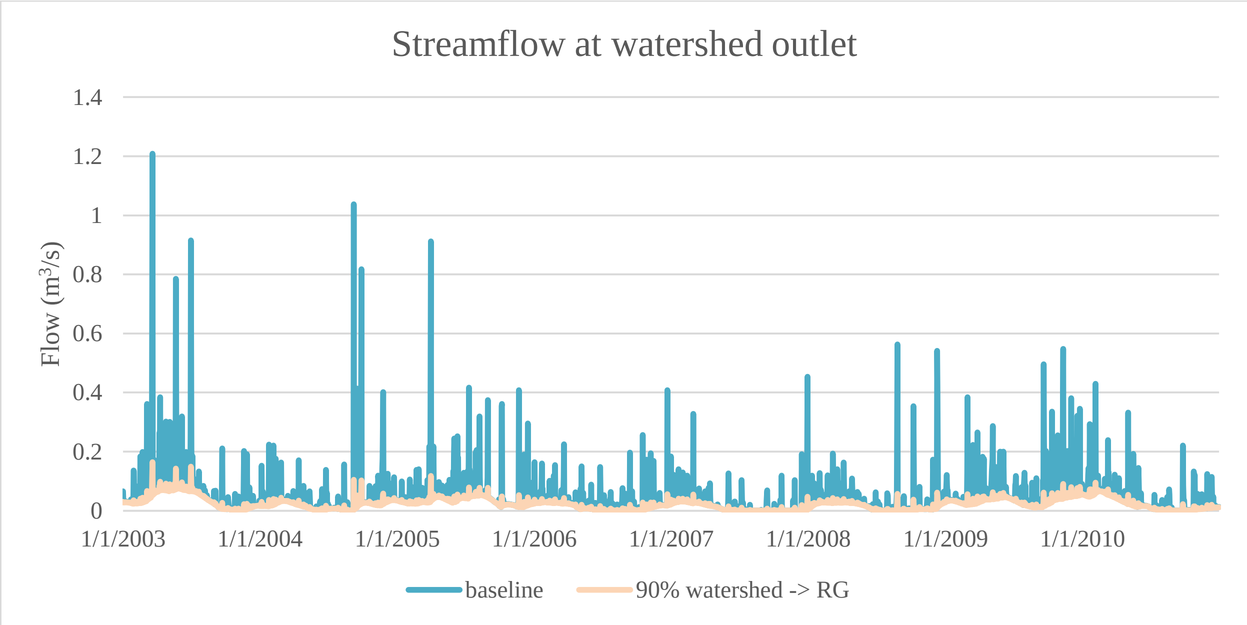

Figure 3.8. Simulation of 90% of a watershed's runoff treated by rain gardens

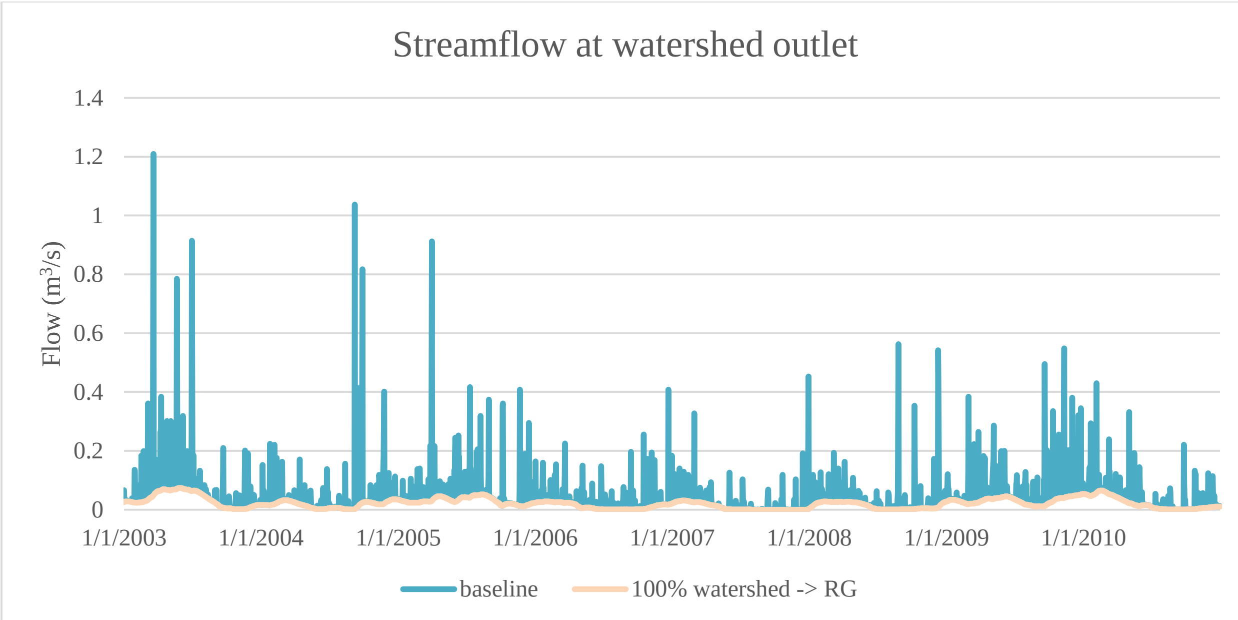

Figure 3.9. Simulation of 100% of a watershed's runoff treated by rain gardens

The 0% rain garden scenario is the baseline, shown in Figure 3.3, against which reductions in runoff can be compared. When 1% of runoff is channeled through rain gardens, shown in Figure 3.4, there is not a noticeable reduction in peak discharge at the watershed's outlet. This lack of reduction is not surprising, as a very small amount of rain garden cannot be expected to handle an entire watershed's worth of impervious surfaces. When 10% of a watershed's runoff is directed into rain gardens, shown in Figure 3.5, large storm peak discharges are reduced on average by 10%. With 30% of runoff flowing through rain gardens, average peak flow is reduced by 30%, which is a desirable target according to Atlanta stormwater recommendations for individual properties (Rayburn & Rutherford 2013), and average overall flow is reduced by 10%.

With higher percentages of runoff flowing through rain gardens, peak flow is even further reduced. The scenario in which 50% of runoff from a watershed flows through rain gardens reduces peak discharges by an average of 45%. With 90% of runoff flowing into rain gardens, most storm peak discharges are eliminated, while 100% of runoff flowing through rain gardens brings flow down to the baseflow, virtually eliminating all stormwater peaks. The more runoff that flows through rain gardens, the less peak discharge, but smaller percentages of rain garden coverage may be the best goal to strive for in terms of making a real difference downstream that matches pre-development hydrology, as explained in the following section.

Ideal rain garden treatment based on pre-development conditions

Many stormwater management regulations are shifting their goals from achieving a given percentage reduction in pollutants to matching pre-development conditions. This change reflects the natural heterogeneity in runoff quality and quantity of different pre-development land uses, slopes, and underlying soils, and also prevents stormwater controls from being oversized to handle infrequent large storm events (USEPA 2011, Rayburn & Rutherford 2013). While the post-development goal of eliminating all stormwater peaks may seem like a good one to strive for, it is possible to do too much; even a natural undisturbed forest will generate some runoff when large storm events produce precipitation in exceedance of the soil's infiltration capabilities. Because rain gardens can hold a small pool of water before releasing it to streams, they can potentially dampen storm discharge peaks that would cause a natural forested area to generate runoff. Thus, the modeled scenarios in which rain gardens dampen out nearly all stormwater peaks might unnecessarily surpass the stormwater control that was provided by the historical pre-development land. The ideal amount of rain garden coverage would match the pre-development stormwater control without over-treating the discharges.

To determine what amount of rain garden coverage is in accordance with pre-development in Athens, I ran a SWAT simulation in which the Lily Branch watershed had 100% deciduous forested land use, a reasonable approximation for historical Athens. As anticipated, the forested land cover provides runoff control for the majority of storm events but does not entirely dampen out peak discharges for several large storm events, as seen in Figure 3.10. Comparing this forested simulation with the treatment of 100% of a watershed's runoff by rain gardens, it appears that too much rain garden treatment can go beyond that provided by a pre-development forest, shown in Figure 3.11. When 100% of the runoff flows into rain gardens, there are no storm discharge peaks, whereas the forested pre-development land exhibits over a dozen large storm peak flows over time.

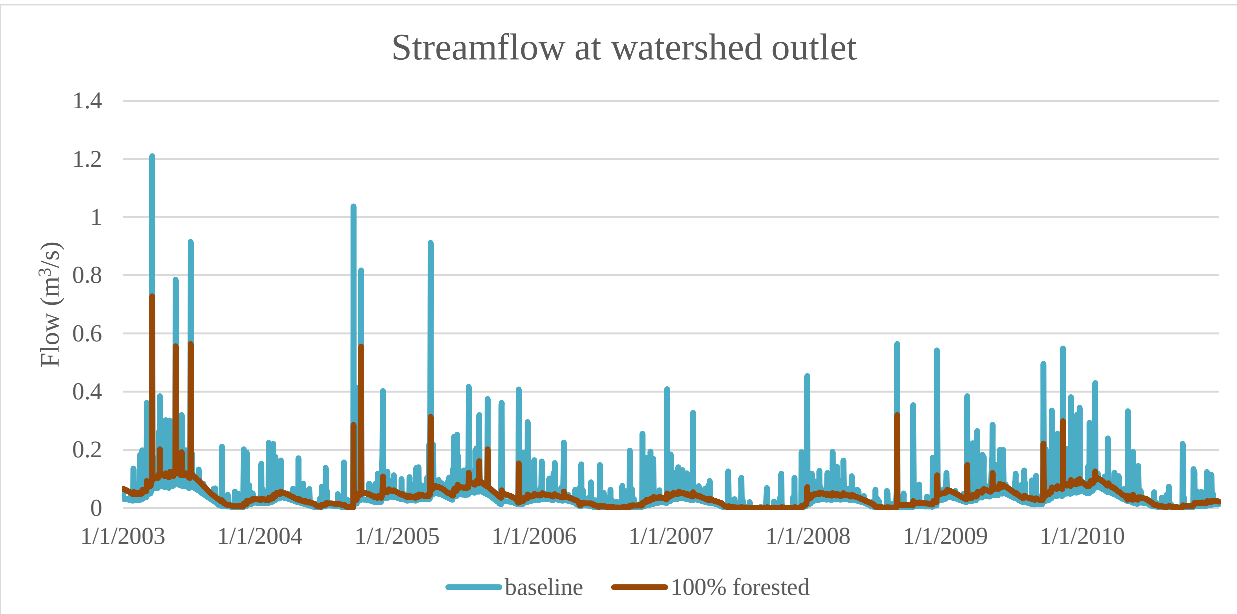

Figure 3.10. Simulation of watershed with 100% forested land cover

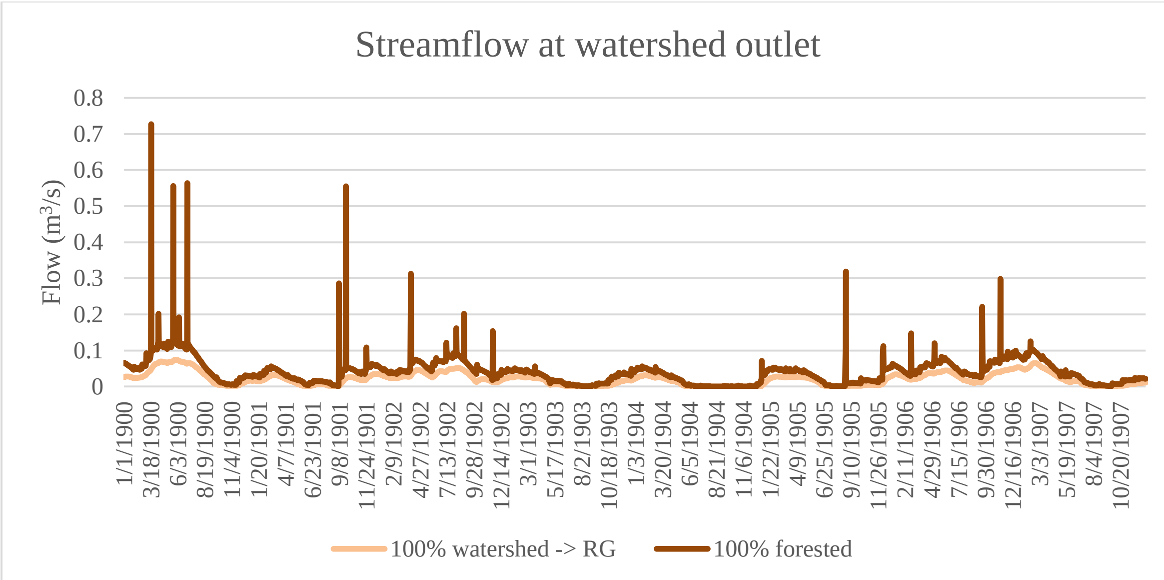

Figure 3.11. Simulations of forested watershed and 100% of runoff treated by rain gardens

To find the ideal percentage treatment of runoff by rain gardens, I calculated the number of times a given rain garden scenario exceeded the stormwater control provided by the pre-development land use. Using a threshold of 1.3 m^3/s, above which I considered the discharge to be a runoff peak based on the forested hydrograph, I found that when 30% of the runoff in a watershed is treated by rain gardens, there were no exceedances or over-treatments. With 40% and 50% runoff treatment, there were only two and six exceedances, respectively, and 90% treatment had 15 exceedances where rain gardens provided more control than a natural forest. The 30% scenario is shown alongside the forested simulation in Figure 3.12. This runoff percentage is encouraging because it is certainly more tractable to treat 30% of a watershed's runoff with rain gardens rather than 100% of the runoff.

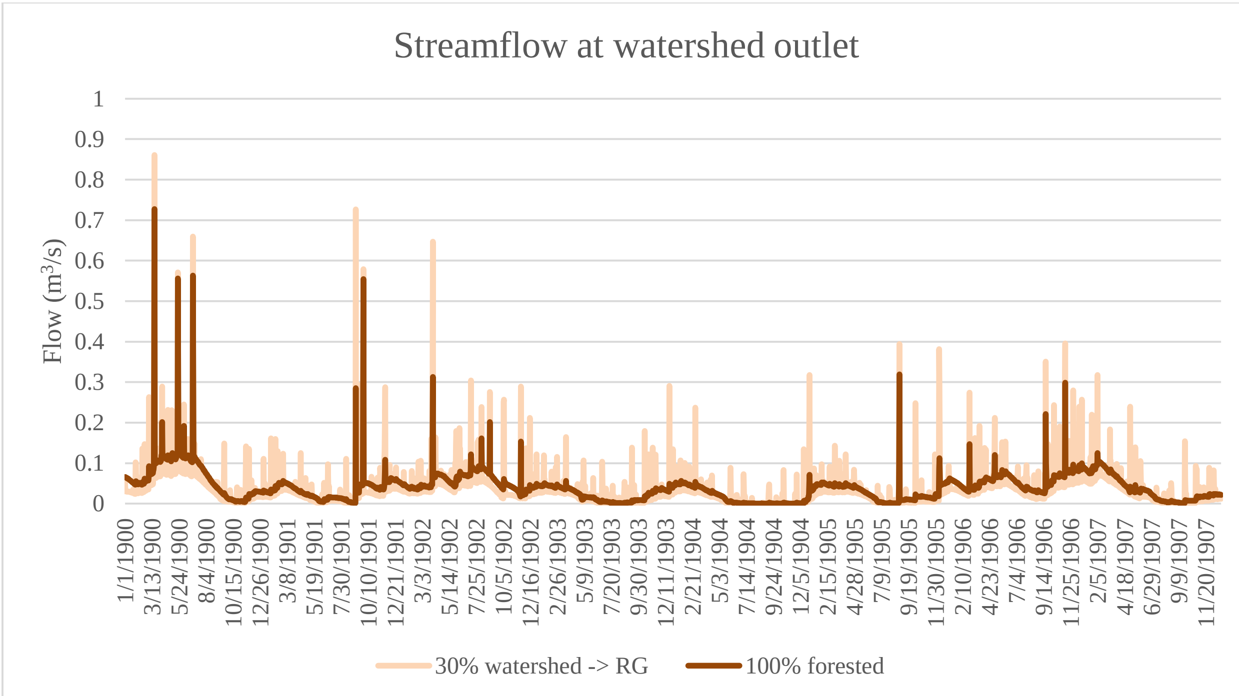

Figure 3.12. Simulations of forested watershed and 30% of runoff treated by rain gardens

Individual subbasins as rain gardens

The model was not calibrated because no gauge data were available for Lily Branch. There is no USGS gauge for such a small stream, and a level logger would need to be in place for several years to yield enough useful information to fully calibrate the model.

Because large-scale calibration was not available for comparing SWAT results to real measurements, I compared SWAT's approximations for rain gardens with actual measurements from the Lily Branch rain garden, described in the previous chapter. In particular, I compared modeled and actual reductions in peak discharge and volume. I used SWAT to separate the watershed into 17 subbasins based on the DEM, and for each of four of these subbasins representing different dominant land use types, I ran a simulation in which 100% of the subbasin's runoff was routed through rain gardens. I then compared the streamflow at the subbasin's outlet for this scenario against the streamflow at the subbasin's outlet for the original baseline scenario. In this manner, I modeled each subbasin as if it were one giant rain garden, and the different land uses help represent rain gardens in different settings.

The subbasins were intentionally chosen to be zero-order catchments, or headwaters subbasins for Lily Branch, so little to no flow entered the stream above them, and the flow exiting them was due to their runoff and subsurface contributions. The primary land uses are listed in Table 3.3.

Figure 3.13 shows an example of Subbasin 4 with the baseline streamflow at its outlet and streamflow with 100% of its runoff routed through rain gardens. All subbasins showed similar behavior, with storm peaks eliminated. The average reductions across all subbasins were as follows: a 28% reduction in overall flow, 82% reduction in peak flows, and 43% reduction in volume, with individual reductions listed in Table 3.3 alongside primary land use.

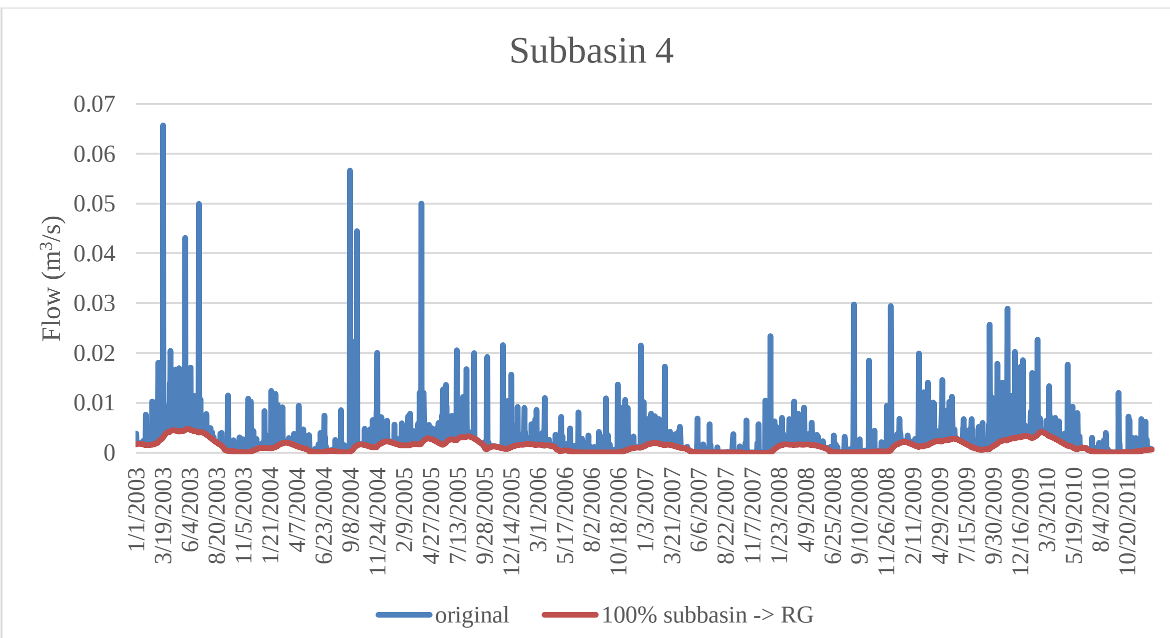

Figure 3.13. Subbasin 4 with 100% of runoff routed through rain gardens

Table 3.3. Primary land use of selected headwaters subbasins in Lily Branch watershed

Subbasin	**Primary Land Use**	**Average % flow reduction**	**Average % peak reduction**	**Average volume reduction**
4	Urban medium density	27	85	44
14	Urban low density	21	70	26
15	Urban high density	25	89	54
16	Deciduous forest	38	83	48

The average observed peak reductions in the Lily Branch rain garden were 91%, which is higher than estimated by SWAT's rain gardens. This discrepancy is partly due to the hydraulic conductivity of wetlands in SWAT, which are not as high as in a real rain garden even when set to the maximum permitted value. A simple modification in SWAT allowing for greater hydraulic conductivity of wetlands could provide a better approximation for rain gardens. Similarly, volume reduction in the individual subbasin simulations was lower than the Lily Branch rain garden's average of 65% across 10 measured storms. Thus, using SWAT's wetlands as an approximation for rain gardens tends to provide more of a worst-case scenario, modeling rain gardens that do a mediocre job of mitigating peak flows.

Modeling rain gardens in an additional watershed

I repeated the modeling process for another small, local Athens watershed to demonstrate rain garden impacts for a watershed with different land use. This watershed is Tallassee Creek, located to the northwest of Athens and pictured in Figure 3.14. Tallassee is a less urbanized watershed, 588 acres large, with over 60% forested and only 17% urbanized land based on NLCD data, listed in Table 3.4.

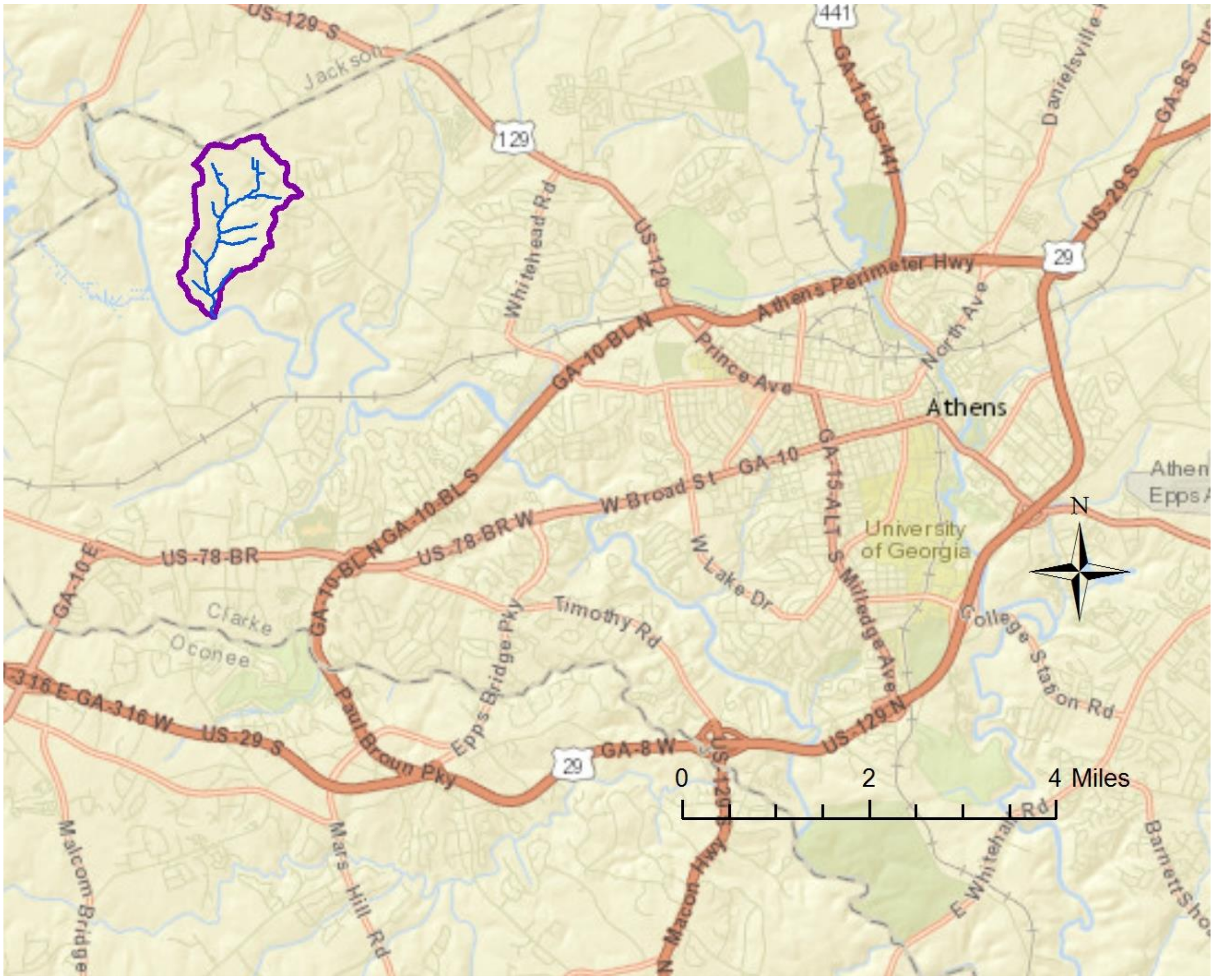

Figure 3.14. Tallassee Creek watershed, outlined in purple

Table 3.4. Land use in Tallassee Creek watershed

Land use type	**Percentage of watershed**
Urban high density	0.97
Urban medium density	1.73
Urban low density	14.56
Industrial	0.28
Deciduous forest	53.03
Forested wetland	1.14
Evergreen forest	6.81
Mixed forest	1.15
Grassland	4.87
Pasture and hay	14.6

Because of its less urban nature, Tallassee showed less flashy behavior in its baseline simulation and generally experienced lower discharges than Lily Branch did, despite being a watershed of similar size and baseflow. Additional simulations routing runoff through rain gardens eliminated those peaks due to storm runoff, shown alongside the baseline simulation in Figure 3.15. Much of the Tallassee watershed would be unsuitable for the creation of artificial wetlands or rain gardens due to its high gradient in places. Not only is much of the terrain unsuitable for rain gardens, but since it is mostly forested, the Tallassee watershed does not generate high levels of runoff as frequently as urban Lily Branch. Widespread rain garden installation across this watershed would over-treat runoff and thus appears unnecessary.

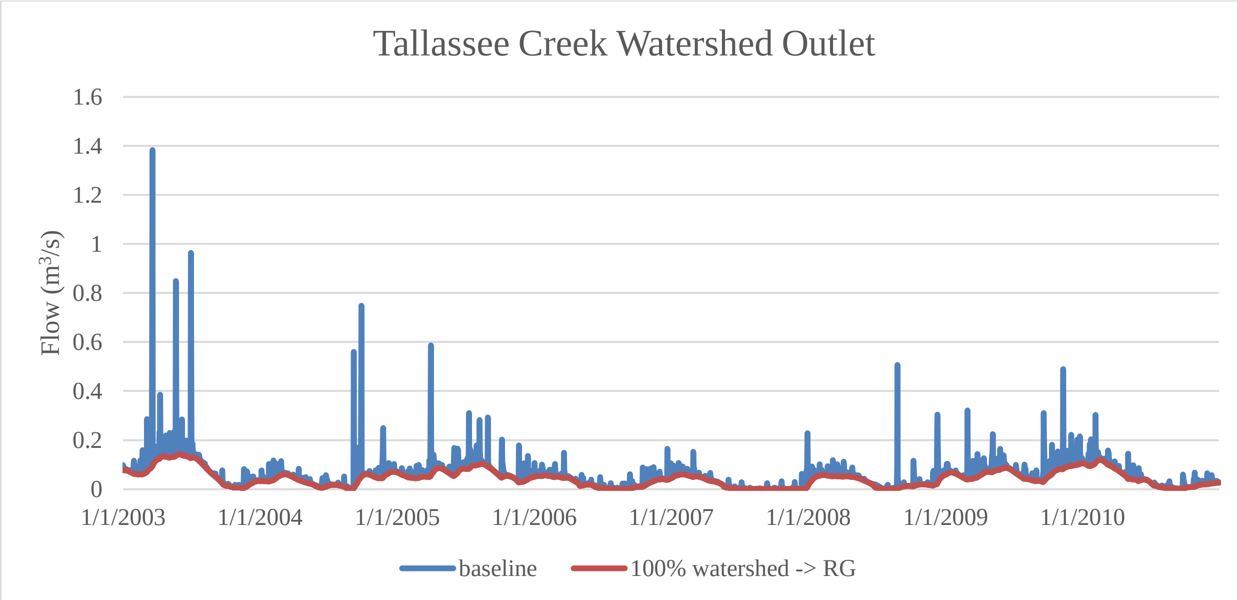

Figure 3.15. Simulated Tallassee runoff hydrographs

Model issues

The placement of rain gardens may have just as important an effect on runoff as the quantity of them. Size may also matter when it comes to bioretention; it is possible that smaller numbers of larger bioretention, wetland, or forest areas may have a greater impact on water quantity and quality than larger numbers of small-sized green spaces. The scenarios modeled in SWAT focus on the amount of runoff treated by rain gardens, not the combined quantity, size, or placement of rain gardens, factors which ultimately have an impact on the amount of runoff treated. The advantages to SWAT's distributed rain garden simulation method is that large watersheds can be simulated without having to physically place many rain gardens on the map, but the disadvantage is that comparing specific scenarios for rain garden design and placement cannot be done using this method. Future studies looking at watershed-scale effects may benefit from the use of different software, particularly programs targeted towards urban environments.

Conclusion

High-density land use makes up a little over a quarter of the Lily Branch watershed, and large-scale routing of runoff into rain gardens might seem infeasible in such a well-established urban area. However, urban land use is always in flux with ongoing development; municipalities are encouraging the installation of bioretention cells, constructed wetlands, and green roofs by property owners to reduce the amount of impervious surfaces in a watershed, and campus construction and building modifications are a constant part of life. As properties change hands and find new uses, their potential contributions to water quality improvements can be considered, and rain gardens may be incorporated into the property.

Rain gardens are frequently installed as demonstration projects. As shown through the SWAT simulations, an individual rain garden located in a large watershed might not impact stream water quality and quantity on its own. However, with infiltration provided by many rain gardens together, streams will see improvements. The level of runoff treatment by rain gardens necessary to attain pre-development hydrology is watershed-dependent, and could range from a very small percentage to greater than 50%. In general, the more urbanized a watershed, the more its streams will benefit from runoff treatment by rain gardens. The goal in urban environments should be to continue increasing LID coverage, ultimately achieving sufficient infiltration and detention to return a watershed to its pre-development hydrology and lessen impacts to urban streams.

CHAPTER 4

POLICY IMPLICATIONS FOR RAIN GARDENS

The preceding chapters of this thesis have focused specifically on rain gardens as a stormwater management tool. Rain gardens are effective at mitigating peak flows and pollutants, cost-effective, aesthetically-pleasing, and flexible in their design and location. This chapter takes a wider scope in looking at low-impact development (LID) as a whole, of which rain gardens are just one tool, and the role of policy in the use of LID.

Despite proven effectiveness, LID is not always the tool of choice for managing stormwater, as shown by the prevalence of conventional "grey" stormwater practices, such as concrete detention basins and curb-and-gutter systems, that continue to be installed as stormwater management for new development. LID adoption is often stunted due to perceived barriers, with a general unfamiliarity with LID techniques leading to questions about their efficacy and financial viability. Over the past 20 years, researchers and academics have worked hand-in-hand with municipalities to study, install, and raise awareness about LID and green infrastructure, with the end result that LID is gradually becoming more accepted and commonplace. It is likely that over time LID will become the default tool of choice for designers and developers over grey infrastructure.

The first step to increasing the use of LID is to understand the current problems and barriers that prevent its universal adoption. Researchers ranging across the country from Oregon, California, and New Mexico to Florida, North Carolina, and Maryland largely agree on the problems, though they may offer different classifications and solutions to the problems. A combined study of LID use in the United States and Australia identified seven clear and unique potential barriers to LID adoption: uncertainties in performance and cost, insufficient engineering standards and guidelines, fragmented responsibilities, lack of institutional capacity, lack of legislative mandate, lack of funding and effective market incentives, and resistance to change (Roy et al. 2008). An additional barrier not mentioned in that study is site suitability and availability. Since the publication of that study, some of these barriers have been effectively tackled and are swiftly becoming non-issues, while some remain problematic. This chapter will examine these barriers, relate them to findings across other studies, consider if they are still problematic, and discuss how government and policy can promote and increase the use of LID.

Uncertainties in performance and cost

A major question in whether or not to install LID is the question of effectiveness, that is, how well do LID techniques work at mitigating stormwater. As so-called "hardscape" or "grey" infrastructure is older and well-understood, it may feel like taking a leap of faith to fully embrace LID. However, performance studies on the behavior of LID practices both in the lab and in the field are abundant, and they always point to LID as being highly effective (Roy-Poirier 2010, Dietz 2007, USEPA 2000). Published studies do not necessarily make the jump from the academic world to the world of practitioners, and it is this knowledge transfer gap that extension and outreach specialists aim to remedy.

Extension agents at southeastern land-grant universities such as the University of Georgia, Auburn University, North Carolina State University, University of Florida, and Clemson University have extensive relations with researchers, farmers, local governments, and other practitioners including landscapers. These university extension agents conduct training workshops, engage in research, and publish information in non-academic venues to spread knowledge about the relationships between water quality and agricultural and development practices. Groups such as the Center for Watershed Protection offer training and information about stormwater and LID via webinars and direct action in communities. US EPA sponsors frequent competitions and grants that incorporate the use of LID in urban planning and revitalization. These multifaceted approaches attempt to spread information about LID within different realms of the community.

Another major barrier to the adoption of LID is that of finance, though this barrier is often simply a perceived one rather than a real one. The fear that LID is bad for business or too costly is often not founded in reality. Individual LID components can cost more than their conventional counterparts, and some LID designs have a higher overall cost than “grey” ones, but when one weighs the overall design costs and benefits, there are often clear advantages to using LID. Reduced costs sometimes arise from the overall LID system design, despite increased costs in some individual components, and benefits such as improved water quality should not be excluded. Several studies have calculated the short-term and long-term cost savings of LID over conventional infrastructure, and they reveal that LID installations frequently provide both short- and long-term cost savings.

One study developed a set of spreadsheets to estimate the potential life-cycle costs of various combined sewer overflow system (CSO) designs (Cohen et al. 2012). The authors examined the costs for a combined “grey/green” approach over a conventional grey stormwater system in Kansas City, Missouri. The grey/green combination utilized tunnels and rain gardens and was estimated to save more than $35 million over the course of a projected 50-year lifetime due to fewer concrete tunnels and basins.

A study of a residential development in North Carolina details some cost-saving measures of LID (NC Extension 2009). A major cost-saving effort in the design of Drover's Road Preserve was foregoing the traditional curb-and-gutter system; in its place the designers used bioswales, which were cheaper than the curb system and helped offset the added costs for some of the other LID installations. The lay of the land was carefully considered in the design, with steep slopes being avoided and stream crossings minimized. Road widths were made smaller, reducing impervious surface area and the cost of pavement. Additionally, over half of the land was put under a conservation easement, which eased the property tax burden.

A study in Wake County, North Carolina, compared the costs of redesigning a residential development using conventional versus LID infrastructure (NC Extension 2009). The study calculated that while some individual components of LID design such as bioswales may cost more than their conventional equivalent, or in this case a dry pond, foregoing conventional aspects of design such as curb-and-gutters and minimizing impervious concrete surfaces can cut costs and help pay for those components that might otherwise prove more expensive than traditional components. The financial benefits of pollutant reduction were not estimated, though failure of conventional infrastructure to reduce nutrients such as nitrogen and phosphorus could encounter a mitigation penalty, thus further increasing the financial benefits of LID.

Insufficient engineering standards

The use of LID in development and urban planning has only become prevalent over the past 20 years (Dietz 2007), and the science of LID is changing and advancing at a rapid pace (NC Extension 2009). Roy et al. argue that engineering standards for stormwater management often hinder the implementation of LID. An example of these standards is the requirement that an installation reduce peak flow by 30% and reduce total suspended solids (TSS) by 80%. By focusing on peak flow mitigation or removal of some percentage of pollutants, these standards leave the door open for conventional techniques that do the bare minimum and are just "good enough" at dealing with flow and specific pollutants, when good LID installations can remove nearly all pollutants. Sometimes these standards require that stormwater basins be sized and built regardless of the LID coverage of a site; they simply do not yet incorporate LID into the standards.

Many states are gradually changing their stormwater standards, but even when the standards support LID use, engineers and designers may feel that there is a dearth of support available to guide them in utilizing LID. Practitioners with the desire to install LID lament the lack of stormwater performance standards, design templates, and manuals (Kaplan n.d.). However, this situation is rapidly becoming a non-issue as more government entities and organizations publish their own LID recommendations that are readily accessible by any interested parties.

Appropriate standards for stormwater management and guidance manuals regarding the design and construction of LID practices should be developed by local or state governments and should be based on recommendations from the research community. These standards and manuals will likely need to change over time as the science of LID matures. Numerous states, counties, cities, non-profits, and consulting firms have written their own LID construction and permitting guides and manuals, ranging from Maryland to Arizona; Philadelphia, Pennsylvania to Nashville, Tennessee; and American Rivers to Canada's Credit Valley Conservation.

The Center for Watershed Protection has published two lengthy manuals for the state of Georgia, one of which educates about general stormwater management, and the second of which provides technical engineering guidance for installing both conventional stormwater Best

Management Practices (BMPs) and LID practices. The Atlanta Regional Commission (ARC) is updating these stormwater management manuals to further encourage LID installation, with an expected delivery date of fall 2015.

Fragmented responsibilities

A common dilemma with LID installations is which party or parties should bear the ongoing and future cost and maintenance responsibilities. Who must maintain an LID installation and ensure that it is functioning properly over time can be complicated by who installed the LID, where, and why. Similar questions exist about the responsibility for maintaining conventional stormwater practices, but the “green” aspect of LID adds additional considerations because the installations operate optimally when their plants and soil are maintained in a particular range of conditions. Examples of unclear responsibility include the following scenarios: a local municipality or non-profit organization installs a rain garden as a demonstration on private land; private land owners receive water quality credits or stormwater fee reductions for their LID installations; a rain garden is installed on “common space” in a residential neighborhood to beautify the space and treat road runoff.

There are several possible policy options with regards to LID maintenance. First, long-term responsibility can be relegated to any number of different parties, including an individual homeowner, local government, Home Owners Association (HOA), stormwater utility, or Soil and Water Conservation District (NC Extension 2009). Once responsibility is determined, the issue of maintenance can be handled using various tools: local government-issued operating permits with maintenance and renewal requirements; legally enforceable maintenance plans; and legal requirements that the developer or landowner must provide for future LID maintenance costs. Regardless of who ends up with responsibility for the LID, proper education is necessary for responsible parties to ensure that their LID is working properly.

Several studies discuss how the responsibility and maintenance issues have been handled in some of these actual complex scenarios. The residential Tonbo Meadow development in North Carolina incorporated a number of LID installations onto shared community land, including rain gardens, vegetated swales, and a constructed wetland. The upkeep and maintenance for these installations ultimately fell under the control of the HOA (NC Extension 2009). When a HOA is designated as the primary manager for an LID installation, a backup should be in place in case the HOA becomes defunct; such backup solutions could include an agreement that local governments will levy additional property taxes to cover the maintenance costs (Jaffe et al. 2010).

As part of a large-scale installation of rain gardens across private landowners' lots, the North Carolina Backyard Rain Garden Program covered installation costs of rain gardens and provided education to homeowners, who were then left in charge of maintaining the new rain gardens (Woodward et al. 2008). The follow-up study of these rain gardens is encouraging regarding the long-term efficacy of privately-maintained gardens. After two years, 73 rain gardens were revisited and inspected, and 56 of them (77%) were deemed to be in "good" or "fair" condition, providing some water quality benefits. The majority of the failures occurred at schools, where presumably the installations were forgotten over breaks or gradually neglected over time as teachers focused their attention elsewhere. Out of 31 homeowners who elected to have a garden due to an interest in gardening, environmental issues, or their proximity to a community lake, only one experienced a failure during the study period. Such statistics seem promising, as privately-maintained rain gardens can continue to make a difference in water quality after their installation without the need for much external assistance. A recommendation to the Illinois Environmental Protection Agency suggests that private land owners enter into contractual agreements for maintaining LID installations and that these contracts be passed down with land records for the property through all future owners (Jaffe et al. 2010).

Lack of institutional capacity

Roy et al. describe the lack of institutional capacity, i.e., funding and manpower, for local governments to undertake regulation and monitoring of LID projects to ensure that they are functioning properly. While there is likely some truth to this lack of capacity, such monitoring and reporting requirements could be pushed onto the responsible party for the LID, as mentioned in the above section on responsibility.

As conventional stormwater measures are themselves subject to frequent or annual inspections, it seems likely that if institutional capacity is already stretched thin, adding any additional stormwater infrastructure, be it grey or green, will tax the system equally. However, as local governments do not seem to be putting a moratorium on development due to lack of institutional capacity, it is a matter of prioritizing that money and manpower to go towards LID inspections in addition to or with priority over grey ones.

Many counties in North Carolina that mandate LID use for stormwater control require and conduct annual inspections of these installations (Woodward 2008). Additionally, the North Carolina Department of Environment and Natural Resources (NCDENR) offers an Express Permitting Program that allows faster review of LID-friendly project plans and at a reduced permit fee (NC Extension 2009). Thus, such institutional capacity is already available in some locales where priority dictates it.

Roy et al. also claim a lack of LID-related training for engineers, architects, and designers as a problem. Such a widespread lack of knowledge across a spectrum of practitioners is troubling but can be remedied through ongoing educational workshops and demonstrations. Further, with copious research into LID going on at the university level, it is likely that younger generations of these careers will have a broader knowledgebase and will be more familiar with these newer design principles.

Lack of legislative mandate

Kaplan explains that not only is there sometimes a lack of mandate for LID, but sometimes local ordinances unintentionally discourage LID or actually make it illegal (n.d.). For example, requisite setbacks, overly-generous street width and parking ratio requirements, and curb-and-gutter requirements may preclude LID installations (NC Extension 2009). Municipalities can avoid these issues by adding exclusive exemptions or specific directives involving LID that do not stifle homeowners or make the transition to green infrastructure unnecessarily difficult.

Policy and implementation has not quite caught up with LID research; as of 2011 a majority of states did not explicitly require the use of LID (USEPA 2011), with the result that grey infrastructure is still the status quo in many states and municipalities. EPA compiled a summary of the stormwater standards for all 50 states in 2011. Seven states had retention standards that worked towards the capture and infiltration of runoff with the goal of matching post-development hydrology with pre-development hydrology. Other states had less ecologically-matched goals, with reduction requirements of 2-year storm events, 80-90% of annual runoff, or the first one to two inches of runoff, often coupled with required treatment of the first several inches of runoff. Some of these standards were non-regulatory, and some states made exceptions for the explicit retention and treatment requirements if LID measures were being used. Seventeen states applied the same requirements of new development to redevelopment; several more held the same standards for redevelopment provided the property met some minimum threshold size, while a few states laid out explicitly different standards for redevelopment.

Many changes have occurred since the writing of EPA’s summary, including Georgia's stormwater standards. The EPA summary used a 2001 edition of Georgia's State Stormwater Standards, which has been amended with the 2009 publication of a set of coastal recommendations. Georgia's standards apply to newly developed or redeveloped areas of at least an acre in size or to projects smaller than an acre that are part of a larger development. Previous requirements included detention of a 1-year storm for 24 hours, treatment of 85% of annual storms (1.2" rainfalls), and reduction of TSS by 80% on average over the course of a year (AMEC et al. 2001). Additionally, post-development peak discharge could not exceed pre-development peak discharge for the 25-year 24-hour storm event.

The Georgia Coastal Stormwater Supplement is a supplemental guidance document that was published in 2009 specifically for the benefit of Georgia coastal communities (Center for Watershed Protection 2009). The document strongly advises the use of LID for maintaining pre-development hydrology, and goes on to offer guidance on site planning, design, and post-construction management. Development projects are recommended to meet the following stormwater management criteria: attenuate peak flows of 100-year, 24-hour rainfall events; enforce a buffer of at least 25 feet around aquatic resources; detain 1-year, 24-hour events for at least 24 hours; and reduce runoff volume of the first 1.2” of every rainfall event.

Neither the Georgia Stormwater Management Manual nor the Coastal Supplement is regulatory in itself, but municipalities must implement the guidelines laid out by them or a similar set of rules as part of their obligation under the National Pollutant Discharge Elimination System (NPDES). In 2013 the City of Atlanta took one step further and implemented their own Post-Development Stormwater Ordinance, requiring the capture and infiltration of 1.0" of runoff onsite using LID practices (Rayburn & Rutherford 2013). Post-development hydrology must match pre-development hydrology, eliminating the previous need for oversized detention basins intended to capture 100-year floods. As of July 2015, the Atlanta Regional Commission is in the process of updating the Georgia Stormwater Management Manual to incorporate lessons learned from LID installations inspired by the Coastal Supplement. These updates will offer updated information and encouragement for the use of LID practices for stormwater management.

Lack of funding and effective market incentives

While LID designs may end up being more cost-effective than conventional stormwater ones, Roy et al. point out that other factors, including removal of existing infrastructure and training for practitioners, can increase the cost of LID installations, making them less desirable. To offset these costs, incentives can be offered at the local government level through reduction of stormwater fees; faster, cheaper permitting for LID projects; and "cap-and-trade" subsidies for stormwater quality. Government subsidization of LID projects may be justified since treating water quality problems at their source ultimately saves money in the arenas of drinking water and environmental health of streams. It is a cheaper way of meeting water quality standards set by the Clean Water Act and is certainly less complicated than trying to clean up water bodies after they have become impaired.

The Georgia Coastal Supplement outlines potential stormwater credits municipalities could consider, including credits for installations that provide stormwater runoff reduction, water quality protection, aquatic resource protection, overbank flood protection, and extreme flood protection. Credits generated by a LID installation that provides benefits towards these categories could be used to lessen the property's stormwater fee.

New York City provides a success story for the use of government-provided incentives for green roof LID installations. New York City offers tax abatements of approximately $5.23 per square foot with a total value cap of $200,000 (NYC 2013). Additionally, New York City's Green Infrastructure Grant Program has provided $11.5 million since 2011 to assist in the installation of 29 green infrastructure projects. These tax abatements and grant funds allowed the installation of more than 200 LID installations, bringing 1.4% of impervious surfaces in the city under the treatment of LID stormwater practices. The program is growing, and this percentage will increase with time.

Resistance to change

Because of the relative novelty of LID infrastructure, people at all levels of the LID design, approval, and installation process may be hesitant to try something new. Risk-aversion and the fear of litigation are possible drivers of this resistance to change, but the aforementioned barriers of uncertainty in performance and cost also play a major role, despite overwhelming evidence and publications to the contrary. Resistance to change then appears to be a result of the failure of research to make its way into the practitioners' world.

Demonstrations of LID practices are important for providing proof of their success, but also important is recognizing key players who are involved with LID (NC Extension 2009).

Celebrating the efforts of those who work with LID not only boosts the morale of those actively advocating for LID but also provides a trail-blazing role model for the community.

Evidence of this resistant mentality is the ongoing struggle over more stringent stormwater regulations in the City of Chattanooga, Tennessee. Chattanooga is in the process of adopting stricter stormwater rules but has been set back along the way by developers and engineers who claim that anything more than the state minimum regulations is bad for business (Smith 2014). While stricter regulations in Chattanooga's impaired South Chickamauga Creek watershed are intended to help meet federal environmental decrees brought on by the city's ailing combined sewer overflow (CSO) stormwater system, critics argue that the stricter regulations would not be enough to bring the city into compliance on their own and would drive development away from the city. The research into LID efficacy and financial returns do not support this anti-LID sentiment, and thus it appears that Chattanooga's biggest barrier is simply a resistance to change based on lack of LID-related education and experience of older engineers and developers. Public LID demonstration projects and the support of vocal leaders could help to turn the tide of stormwater management in Chattanooga.

Site suitability and availability

One barrier not addressed by Roy et al. is site suitability and availability for LID. While LID is generally effective in most urban settings, certain conditions of the landscape can make it a less suitable choice. In locales where the underlying soil type allows for poor infiltration, adopting LID may require an unreasonable amount of soil augmentation to operate properly. Areas with a wet climate that leaves the soil saturated for long periods of time may also experience poor infiltration rates. Likewise, topography may make LID less viable, as steep slopes with a gradient greater than 5% will not see a noticeable difference with LID (USEPA

2014b). In these cases, conventional “grey” stormwater management practices may be used for flood control without the added benefit of quality control. However, good designs can accommodate these difficulties to an extent, so LID is generally a good choice for urban settings where there is land available.

Land availability for large-scale installations can be difficult to find in a fragmented urban environment, so a small patchwork network of LID may be the only option in these places. In these scenarios it is good to have a large toolkit of LID options, including green roofs and rainwater cisterns, that could more easily be incorporated into densely-built urban areas. Gradual land use change can allow more areas to become available or transition into pervious surfaces with time, so taking advantage of opportunities as they become available is important and necessary to increasing LID coverage.

Role of policy in increasing LID prevalence and conclusion

Water quality is dictated from the top-down by the federal Clean Water Act, and policy initiated from the state level is an effective approach to increasing LID usage; however, it ultimately comes down to a community and its developers and planners to decide how to manage their stormwater. From the Georgia Stormwater Manual, “[g]iven the fact that local communities typically make the land use and development decisions which create runoff problems and the need for stormwater infrastructure, it is at the local level where these problems must be addressed.”

Local governments have the ability to address the above-mentioned barriers through a number of methods. Local governments can lead the way in providing ongoing education, extension, and outreach to developers and homeowners by providing training workshops and guidance for design, installation, and maintenance of LID. Demonstration projects such as visible, publicly-located rain gardens provide concrete examples for the community.

Municipalities and counties also have the power to remove code barriers and make explicit exemptions for LID. First and foremost, they can require that LID be the default tool for managing stormwater. In general, they should modify their codes to reduce impervious surfaces, either by converting impervious to pervious surfaces or by reducing the amount of required pavement. Such reductions can be made by reducing minimum parking ratios, street sizes, and building footprints and by increasing the use of greenways and trails over paved sidewalks. Local governments can also provide explicit exemptions for LID, which includes allowing LID elements to be located in setbacks and removing requirements for detention basins when LID is utilized as stormwater control. The LID installations in the Tonbo Meadow development in Wilmington, North Carolina, could not have happened without the approval of variances for stormwater control using LID (NC Extension 2009). In addition to code and zoning, municipalities can use financial means to promote LID by introducing stormwater fee reductions and incentives.

With increasing knowledge and desire for improved water quality and environmental health, governments can incorporate LID into codes and standards over time. With increasing knowledge and training of the engineers, designers, and landscapers involved in the process, LID installation will become just as commonplace as conventional practices; it just takes time and the dedicated efforts of individuals and policy-makers.

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