AN ANALYSIS OF STORMWATER RETENTION AND DETENTION

OF MODULAR GREEN ROOF BLOCKS

by

ERIC SCHOMMER PROWELL

(Under the Direction of Todd C. Rasmussen)

ABSTRACT

Green roofs, also known as vegetated roofs or roof gardens, use soil and vegetation to retain and detain precipitation on impervious roof tops. While runoff reduction is an accepted benefit of traditional green roofs, not all roofs are amenable to this design. Newly developed modular designs are more versatile, but their stormwater remediation ability requires assessment. This study quantifies water retention and detention by modular green roof blocks. Twelve blocks were monitored for one year using four repetitions of three treatments (reference, non-vegetated, and vegetated). Stormwater retention and detention was compared within and among treatments and to a traditional extensive green roof located adjacently. The modular green roof blocks retained more than 43% of the total precipitation and reduced runoff 60% when compared to the reference treatment. Little difference was observed between the vegetated and non-vegetated treatments suggesting that the sedum vegetation used in this study was insignificant in providing retention and detention. Comparisons between the modular green roof blocks and the traditional green roof showed a greater retention in the traditional green roof.

INDEX WORDS: Green roof, vegetated roof, stormwater runoff

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DEDICATION

I dedicate the following work to my ever supportive family and friends who have motivated me to follow my ambition.

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I would first like to thank St. Louis Metal Works Corporation for donating the modular green roof blocks used in this study. I would also like to thank Home Depot for their generous contribution for building supplies and other materials.

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CHAPTER 1

INTRODUCTION

Background

Stormwater runoff is a major cause of stream degradation in urban environments (Paul and Meyer 2001). Rapid hydraulic response to rainfall results in increased peak discharges, velocities, and stormwater volumes. These increases cause the physical alteration of stream morphology including bank scouring and erosion (Bledsoe 2002; MacRae1997). In addition to physical degradation of urban streams, stormwater runoff from impervious areas contains increased concentrations of pollutants (Brabec et al. 2002). During dry periods, pollutants, including oils, sediments, pesticides, and heavy metals build up on impervious surfaces, especially roadways and construction zones (Mason et al. 1999). When a storm event occurs, the first flush of stormwater often carries dramatically increased concentrations of these pollutants into receiving waters (Bucheli et al. 1998; EPA 2003).

The biological integrity of urban streams is often compromised by these physical and chemical stresses. Studies have shown that aquatic communities in urban areas tend to be more homogenous and dominated by large quantities of very tolerant species (Karr 1999; Miltner et al. 2004; Wang 2001). Many studies are now showing that the presence/absence of sensitive aquatic species is strongly correlated to upstream effective impervious surface (Booth and Jackson 1997; Wenger 2005). In addition to its environmental effects, public health is also threatened by stormwater runoff. Personal injury and death can result when children and unwary motorists are caught in conveyance channels and culverts during peak discharge conditions.

Stormwater Policy

In recent decades, urban stormwater runoff has presented itself as one of the top environmental concerns for management agencies (Villareal 2004). Development activities such as clearing vegetation, mass grading, removing and compacting soils, and construction of impervious surfaces (including buildings, parking lots, and roadways) can increase the amount of stormwater runoff in the watershed (Brabec 2002). In urban areas, increased stormwater runoff can cause increased flooding, stream bank erosion, and degradation of aquatic habitat (EPA 2003).

The mitigation of stormwater runoff is an important national goal. Established as an amendment to The Clean Water Act in 1990, the National Pollutant Discharge Elimination System (NPDES) is a permitting process which allows state and federal authorities to regulate large and medium cities by limiting pollutants allowed to be carried through municipal sewers (Harrison and Stribling 1995; EPA 2001). As part of this program federal and state regulatory programs now require local communities to develop stormwater management programs that address these problems (Harrison and Stribling 1995).

Because of this legislation, Georgia's permitting program for municipal storm sewers requires local governments to develop stormwater management plans. These plans must incorporate the use of Best Management Practices (BMPs), including the use of structural and non-structural controls to mitigate the effects of quantity and quality issues associated with stormwater runoff (GADNR 2002). Non-structural controls generally consist of limiting impervious cover by using better site design guidelines. One example of this would be conservation subdivisions, where higher density construction is allowed if 40% of the site is left undisturbed. Structural controls consist of man-made structures that actually reduce, delay, and purify stormwater leaving a site.

Stormwater Management Strategies

Conventional stormwater management strategies involve routing stormwater from buildings, roadways, and other impervious surfaces to large, centralized facilities where the water can be retained, detained and treated. (Villarreal et al. 2004). A detention pond is probably the most common structure used in this method of stormwater management. This strategy, although effective for attenuating peak flows, extends the duration of stormflows and therefore extends the period of stress on the physical and biological components of stream ecosystems (Booth and Jackson 1997).

Contemporary solutions to stormwater treatment - such as rain gardens, swales and other bio-retention areas - detain, retain, and treat stormwater close to where it is generated. These distributed BMPs work to maintain the natural hydrology of the site by using natural processes - like infiltration - to their advantage, often decreasing the need for detention ponds and other centralized stormwater treatment facilities (EPA 1999). Although these contemporary techniques have proven to be successful tools for minimizing stormwater impacts, land is limited and expensive in ultra-urban settings. The lack of suitable space often excludes infiltration Best Management Practices (BMPs) and other distributed BMP practices that maintain the pre-development hydrology of the site. In these areas, a new approach to stormwater management is necessary.

Green Roofs

Until recently, rooftops had not been considered for greenspace areas. In many cities, rooftops contribute a substantial amount to the total impervious cover. These areas, with high densities of impervious cover, are considered ultra-urban (FHWA, 1999). Advances in green-roof technology have changed the perspective of many stormwater engineers who now consider rooftops in these ultra-urban areas as plausible greenspace.

Green roofs - also known as vegetated roofs or roof gardens - are simply defined as roofs that have vegetation on top (Markham and Walles 2003). In ultra-urban areas, where rooftops contribute a substantial amount to total impervious surface, green roofs have been used to remediate stormwater runoff.

Studies have shown that green roofs significantly decrease the amount of runoff from rooftops, storing much of the precipitation volume for later evaporation and transpiration (Bengtsson et al. 2005). In cases of significant runoff from green roofs, the peaks are delayed relative to runoff from other impervious surfaces, decreasing combined affects of stormwater runoff (Bengtsson 2005). One study, at the University of Georgia, utilized a traditional extensive green roof 7.5 cm thick. This study, conducted over 13 months, showed an 80% reduction in total stormwater runoff volumes and average peak delays of 18 minutes when compared to a convention gravel ballast rooftop (Carter and Rasmussen 2005).

Reduction in stormwater runoff is an accepted benefit of traditional extensive green roofs, but these roofs have drawbacks because of design limitations. New developments in technology have led to modular designs that are more versatile. These modular designs - although more conducive to widespread utilization - have not been evaluated for their stormwater remediation ability.

Objectives

The five objectives of this study are to:

1) Quantify stormwater retention of modular green roof blocks;
2) Explore detention and peak attenuation capabilities of modular green roof blocks;
3) Determine the role of vegetation in retaining and detaining stormwater from modular green roof blocks;
4) Determine if modular green roof blocks retain stormwater as efficiently as traditional extensive green roofs;
5) Develop a process based model to simulate hydraulic response of modular green roof blocks so results can be applicable to other regions.

Organization

This thesis is organized into six chapters. The first chapter defines the problem and provides an overview of the research goals. The second chapter provides an overview of green roofs and summarizes previous research related to green roof hydrology and water quality. The third chapter presents the research methods employed in this study. The fourth chapter provides research results. The fifth chapter summarizes the research results and provides some policy guidance related to the use of modular green roof blocks. The sixth, and final chapter, provides thesis conclusions.

CHAPTER 2

LITERATURE REVIEW

Green Roof Benefits

Green roofs have the ability to attenuate many of the environmental costs associated with urbanization. Specifically, green roofs have been shown to decrease stormwater runoff (Villarreal and Bengtsson 2005), urban heat island effects (Rosenfeld et al. 1998; Wilmers 1990), and heating and cooling costs (Barrio 1998; Eumorfopoulou and Aravantinos 1998; Niachou et al. 2001; Theodosiou 2003). Although often considered a purely aesthetic contribution to the urban landscape (Kohler et al. 2002), research shows there are significant environmental and financial benefits related to green roofs. (Wong et al. 2003). Reduction in stormwater runoff might be one of the most important benefits associated with green roofs (Mentens et al. 2005). While reducing stormwater infrastructure costs (Bengtsson et al. 2005), green roofs can also address quantity and quality issues associated with stormwater that chronically degrade urban streams.

Green roofs are popular in many European countries like Germany, Austria, France, Norway, Sweden, and Switzerland. Sweden's stormwater Best Management Practices (BMPs) include the use of green roofs for reducing quantity and timing of runoff to receiving waters (Villarreal and Bengtsson 2005). In Germany, seven percent of newly constructed roofs are vegetated, and it is estimated that twelve percent of flat roofs in the country have vegetation on top (Kohler et al. 2002; MSU 2006). These percentages are continuing to grow every year in

Germany as the green roof industry attempts to keep up with demand (MSU 2006). Green roofs are not as common in the United States (Carter and Rasmussen 2005). The limited awareness regarding green roofs, higher installation costs, limited data highlighting the benefits they provide, no industry to build them, and a no government incentives or tax breaks have probably contributed to their absence in the United States (MSU 2006). Although many obstacles stand in the way of urban rooftop greening in the United States, with innovative research, outreach programs, and policy guidance green roof application can flourish here as it has in Europe.

Traditionally, there are two types of green roofs, extensive and intensive (Bengtsson et al. 2005). Extensive green roofs are characterized by their low weight, shallow soil (<30 cm), and minimal maintenance (Bengtsson et al. 2005). Intensive green roofs have a greater weight and soil depth (>30 cm), with higher maintenance requirements (Bengtsson et al. 2005). Both extensive and intensive roof types generally require waterproofing membranes integrated with a water retention liner and a multilayered soil support system (Figure 2.1). Traditional built-in-place green roofs, or built-up-roofs (BURs), have certain inherent limitations, including i) complicated engineering and logistics associated with their installation, and ii) complexity of maintenance and repair during the lifetime of the roof (Markham and Walles 2003). Expensive materials, installation costs, and upkeep have discouraged many from investing in green roof technology.

Recent developments in green roof technology have addressed these limitations and reduced project costs by creating modular extensive systems. Modular green roofs are self-contained portable blocks that simply sit on the existing rooftop (St. Louis MWC 2005). The bottoms of the blocks are outfitted with drain holes and no waterproofing membranes or water retention liners are necessary. This limits material costs to the modular blocks, soil mix, and vegetation, and no expertise is necessary for installation.

Green Roof Research

Green roof research on storm water detention and retention is still in its infancy. With the exception of conference proceeding and popular magazines, published literature on the effectiveness of green roofs as stormwater remediation tools is currently limited (Taylor 2003). . There are fewer than ten published journal articles available in English and only three of these articles conducted their research from within the United States. All of these studies were conducted using extensive style green roofs, which included the use of waterproofing membranes, water retention liners, and between 2 - 8 cm of growing media. Reductions in stormwater were variable from study to study, depending on study site, climate and depth of soil. Generally, research shows traditional extensive green roofs reduce runoff between 50 - 80 percent (Kohler et al. 2002; Monterusso et al. 2004; Bengtsson 2005; Bengtsson et al. 2005; Mentens et al. 2005; VanWoert et al. 2005; and Villarreal and Bengtsson 2005).

A recent study at the University of Georgia, conducted by Carter and Rasmussen (2005), used a paired watershed approach comparing a conventional gravel ballast roof and a traditional extensive green roof (Figure 2.2). This study used large test plots, 43 m^2, to test the hydraulic response of green roofs. A study of this magnitude had not yet been presented in the literature because of the difficulties associated with measuring runoff from roof sizes of this caliber. In this experiment, a two-stage riser system using an open orifice design allowed for the automated monitoring system to be utilized. The green roof used in this study followed the design of Figure 2.1, was 7.5 cm thick, and comprised of various sedum species. Results from this study showed that the green roof decreased runoff volumes 80% when compared to the conventional roof (Carter and Rasmussen 2005). Results also showed that the green roof increased time to peak by an average of 18 minutes and provided peak flow attenuation for most storms (Carter and Rasmussen 2005).

Another recent study, by Vanwoert et al. (2005) from Michigan State University, has to date presented the most quantifiable data for stormwater retention of green roofs, and evaporation and transpiration processes. This study quantified the differences between an extensive green roof, an extensive green roof without vegetation, and a standard flat gravel roof in a replicated study (VanWoert et al. 2005). The substrate of the extensive green roof was comprised of ~40 percent water retention material and ~60 percent soil (VanWoert et al. 2005). Vegetation was comprised of various sedum species, which are succulent plants that are highly tolerant to drought. Results showed that the green roofs retained ~60 percent of the total rainfall during a two-month study (VanWoert et al. 2005). However, the extensive green roof without vegetation showed little difference to the roof with vegetation, suggesting that evaporation is the dominant process affecting the water balance (VanWoert et al. 2005).

Green Roof Modeling

Background

Simulating stormwater runoff from green roofs is necessary for widespread application of limited data sets. In order for elected officials, management agencies, and engineers to make competent decisions involving green roof deployment, a model is necessary that simulates runoff based on a set of given meteorological conditions. Two different approaches to simulating the hydraulic response of green roofs have been attempted by two recent studies at the University of Georgia, Athens.

Carter and Rasmussen (2006) used precipitation and runoff data to develop a Curve Number for a traditional extensive green roof. The SCS Curve Number Method is a commonly used method for determining runoff volumes based on soil type and land use (Dunne and Leopold 1978). The simplicity of this method has led to its widespread application in stormwater management and therefore makes its application to green roofs very appealing. It simply uses green roofs as an alternative land use that is given a Curve Number when modeling runoff from a site. Although this method works well when describing runoff characteristic across a watershed, using it to determine runoff at the roof scale presents some issues. The main problem associated with this approach is that it does not take into account antecedent moisture conditions, which are the driving force affecting the hydraulic response of green roofs for a particular event.

Alternatively, Hilton et al. (2006) used Hydrus -1D to predict soil hydraulic properties and flow through modular green roof blocks using runoff data collected from the study presented in this Thesis. This approach required input parameters including: Volumetric water content at field capacity, wilting point, potential evapotranspiration, and rainfall. Potential evaporation was calculated using Hargreaves method, which requires additional inputs including: average maximum and minimum air temperature, and extraterrestrial radiation (Dunne and Leopold 1978). From this information, a characteristic moisture release curve was developed to determine runoff from the modular green roof blocks. Although this method was successful in estimating runoff at the roof scale, cumbersome laboratory experiments were necessary to determine the moisture release curve associated with the particular soil type.

Alternative Modeling Approach:

Studies have shown that runoff from traditional extensive green roofs usually occurs after the media and vegetation have become saturated (Monterusso 2004; Carter and Rasmussen 2005; VanWoert et al 2005). Between storm events, water stored in media and vegetation evaporates and transpires back into the atmosphere creating storage capacity. During a storm event, the storage that has been made available from evapotranspiration is then replenished. If the amount of storage available is exceeded then runoff occurs from the green roof. When comparing runoff hydrographs from a green roof and conventional rooftop, a delay in runoff (initial abstraction) will occur from the green roof because the storage must first be exceeded (Carter and Rasmussen 2005). After storage is exceeded, the hydrographs are relatively similar.

Based on green roof runoff characteristics observed by others, functionality of the hydraulic response appears to be similar to that simulated in reservoir modeling. Reservoir modeling is confined by the mass balance equation where:

$$\text{Inputs} = \text{Outputs} + \Delta\ \text{Storage}$$

The inputs are any water that is moving into the reservoir (i.e. rainfalll, streams, etc), outputs are water leaving the reservoir (i.e. evaporation, transpiration, water released), and change in storage is the water volume in the reservoir (McCuen 2005). To determine the amount of water exiting through the control structure, all that needs to be determined is excess storage. If the hydraulic response of green roofs revolves around exceeding some predetermined storage, then a reservoir modeling approach should be considered in simulating runoff from green roofs.

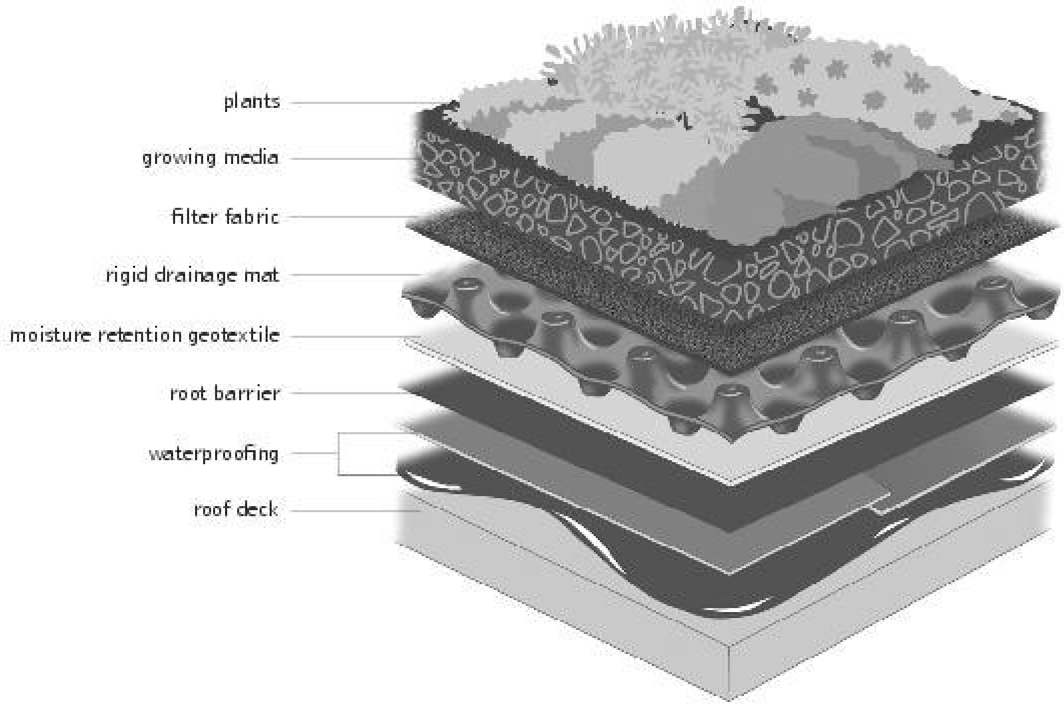

Figure 2.1: Illustration of traditional extensive green roof components.

Figure 2.2: Picture of traditional extensive green roof and typical gravel ballast roof

CHAPTER 3

METHODS

Data collected for this research followed a similar experimental design as VanWoert et al. (2005) using three treatments: i) a vegetated set-up, ii) a non-vegetated set-up, and iii) a reference (no vegetation or growing media). This was completed within the confines of a replicated study using modular green roof blocks that did not include any controlling layers or water retention materials. Data collection also spanned over a one year period so that annual variation could be assessed.

Site Description

This manipulative experiment was conducted on the ground floor rooftop of Boyd Graduate Studies Building at the University of Georgia in Athens, shown in Figures 3.1-3.3. Athens, Georgia sits approximately 250 m above sea level and has a humid subtropical climate with mild winters and hot moist summers (NETSTATE, 2005). Extremely cold temperatures are infrequent and snowfall is rare. The average total annual rainfall is approximately 1,250 mm (NETSTATE, 2005). The wettest month on average is March because of the seasonal cyclonic activity associated with the Southeast during late winter (NETSTATE, 2005). Summers are warm and humid with summer thunderstorms producing short duration, high intensity precipitation events (NETSTATE, 2005).

Site location was selected based on accessibility, structural configuration, and public visibility. The rooftop is bordered by two six-story towers to the east and west, and one three-story building to the north. The northern building has large windows overlooking the rooftop, which allow for green roof viewing. These structures limit sunlight to approximately six hours each day during the summer and nine hours during the winter. The structures may also impact rainfall uniformity, but no data supports this supposition.

Materials

The modular green roof blocks used in this experiment were donated by Saint Louis MetalWorks Company to the University of Georgia. The modular blocks are self contained, portable units that are 60 cm square in size and 10 cm in depth (Figure 3.4). Units are block containers fabricated out of heavy gauge aluminum. Each block had 3 drain holes, located on each side, 1 cm from the bottom; twelve drain holes per block. The green roof blocks used for this experiment consisted of no water proofing layers, drainage materials, root barriers, or filter fabrics; materials were limited to heavy gauge aluminum container, soil mix, and vegetation (Figure 3.5).

These blocks were retrofitted to drain into aluminum collection pans, which then drained into plastic containers (Figure 3.6). Aluminum collection pans were approximately 90 cm square and had a single drain hole leading to the plastic container. Because the aluminum pan extended past the green roof block container, clear plastic was cut, wrapped, and attached to the block and pan to avoid direct precipitation outside the experimental unit. These units sat on top of wooden stands that held the containers approximately 30 cm above the existing roof (Figure 3.6). The units were held tight to the wooden stands using elastic cords.

The soil media mix used for this experiment was a low density, highly permeable mix containing 80 percent PermaTill expanded slate and 20 percent organic material, primarily comprised of worm castings. PermaTill expanded slate is a light-weight aggregate that forms a well-drained soil profile, while maintaining moisture and nutrients vital for plant survival. Each block was hand filled with approximately 10 cm of engineered media.

White Stonecrop (*Sedum sexangular*) was then planted in the vegetated treatments so the effects of vegetation could be assessed. Four plants were placed in each of the vegetated treatments, as seen in Figure 3.7, in June of 2004; 80% coverage had been obtained by October 2004. Sedums are drought tolerant succulent plants that usually have star-shaped flowers with five petals, five sepals (leafy structure around base of flower), five carpels (seed pods), and ten stamens (male organ) (Radford et al. 1968). They have the ability to take up a substantial amount of water when it is available. They store this water and slowly use it up during times of drought (Radford et al. 1968). *Sedum sexangular* is a perennial that has a white powdery covering (pruinose) that reflects the sun's rays. This physical attribute keeps leaves cooler and reduces moisture loss (Radford et al. 1968). Unlike most plants, the stomata on sedum leaves close up during the day and open up at night. This allows the plant to transpire when temperatures are lowest, limiting excess loss of water (Radford et al. 1968). Plant selection was based on ability to tolerate drought and extreme temperature fluctuations, conducive to rooftop habitats, so irrigation, plant replacement, and other associated maintenance would not be necessary (Monterusso et al. 2005; VanWoert 2005).

Experimental Design

The experiment was a replicated study containing three treatments, four replicates of each treatment. The three modular green roof block treatments, shown in Figure 3.5, are:

1) Reference Treatment (empty block): Contains no soil or plants.
2) Non-Vegetated Treatment: Contains 10 cm of soil, but no plants.
3) Vegetated Treatment: Contains 10 cm of soil and sedum plants.

Twelve available spots on the wooden stands were separated into four groups (blocks) based on rooftop location. Each treatment was randomly assigned a location in each of the four groups using a random number generator, thus achieving a randomized complete block design (Figure 3.6). This design was appropriate due to the possible influence of the study site on distribution of rainfall. The randomized complete block design was used to control for this potential variation along with any other unforeseen extraneous variation.

Data Collection and Analysis

Stormwater collection containers were outfitted with Druck PDCR 1800 pressure transducers. Transducers were mounted inside half inch diameter, one foot long pieces of PVC that were attached to the corner of each container. The PVC covering reduced water level fluctuations during storm events. The transducers were connected to a Campbell Scientific CR23X datalogger, which was programmed to record water depth in millimeters every minute. Pressure transducers were calibrated to sub-millimeter accuracy to decrease measurement error and ensure precision.

For the purposes of this study, runoff was defined as deep percolation or water that leached through the soil, exited through the drain holes, entered the collection containers, and consequently amounted to some depth of water that could be measured. Due to the permeability, and consequent high hydraulic conductivity, surface runoff was never observed. Because the runoff collection containers were irregularly shaped, no direct method could convert depth measurements to volumes. To attain volume measurements, a container was filled incrementally with one liter of water and the water height was recorded at each interval. A polynomial regression equation was then used to relate water depth to volume (Figure 3.7).

$$V = 9 \times 10^{-5}\, d^2 + 0.13252\, d + 0.15142$$

where	d	water depth and
	V	water volume.

Rainfall was continuously collected on the rooftop using two Texas Electronics TR525M tipping bucket rain gauges. Mean rainfall was used for analyses when gauges were both collecting data. Due to equipment failure during December 2004 and January 2005, rain data was used from another campus rooftop location approximately 300 meters to the north.

The twelve blocks were continuously monitored for a twelve-month period, from October 1, 2004 to September 30, 2005. Storm-event separation was performed by requiring an antecedent quiescent (dry) period of one day (24 hours) between runoff events.

Retention data were analyzed for all rain events during the one-year study period. No snowfall occurred throughout the study, but one ice storm did occur and was included in the results. Two of the pressure transducers, one from the vegetated treatment and one from the non-vegetated treatment, were inconsistent in their monitoring levels and would not respond at times.

To ensure data accuracy and precision, these two experimental units were excluded from analysis. Without these two experimental units, analysis consisted of four replicates of the reference treatment, three replicates of the vegetated treatment, and three replicates of the non-vegetated treatment.

Rain events were subjectively divided into categories based on event size: Light (<6 mm), Medium (6-25 mm), Heavy (>25mm). Event size separation was chosen to allow for similar sample sizes across categories. By separating the storms, retention was able to be characterized based on precipitation depth.

Statistical Analyses

Total runoff volume for each individual event was compared within and among treatments using repeated measures analysis of variance (ANOVA). As with any ANOVA, a repeated measures ANOVA tests the equality of means. A repeated measures design is appropriate because data collection involves repeated measures on experimental units under a number of different conditions through time (Littell et al. 1998). As the experimental units are exposed to different conditions, the measurement of the response variable is repeated. A univariate approach to repeated measures ANOVA was used, which basically considers the experimental units as 'whole-plot' units and time as 'sub-plot' units. A Tukey test was then performed to determine which treatments were statistically significant from one another (SAS Institute, 2001). These analyses were performed for the 44 events where runoff occurred for each of the 10 experimental units.

Mean percent reduction was also calculated between the reference and vegetated treatments, as well as the non-vegetated and vegetated treatments for each event in which runoff was recorded. The mean percent reduction was then fitted with errors bars to account for within treatment variation. The error bars represent the maximum and minimum of the vegetated treatment for the representative event.

Three, one-month periods were analyzed at two minute intervals to determine mean values for initial abstraction, peak discharge attenuation and runoff prolongation associated with each of the three treatments. Months were chosen based on time of year and convenience. For the purposes of this study, initial abstraction was defined as the depth of rainfall that occurred before runoff was generated in the representative treatment. Peak discharge attenuation was defined as the reduction in peak runoff measured in the non-vegetated and vegetated treatments relative to the reference treatment. Runoff prolongation was defined as the time the runoff hydrograph was extended by the representative treatment relative to the senescence of rainfall.

Storm peak discharges were obtained using the maximum of the two-minute observations for each storm event. This part of the analysis presented some problems because of the experimental design. Water levels in the containers continuously fluctuated during events due to runoff falling into the container from the green roof blocks. The pressure transducers measured water depth leading to fluctuating levels throughout a storm event. Although peak discharges could be determined, it is not likely that these peaks accurately represent the natural peak discharges associated with modular green roof blocks. Recommendations are made in the discussion that may help others avoid this problem.

The mean retention of the vegetated treatment was also compared to that of a traditional extensive green roof. The traditional extensive green roof is located on the same rooftop, incorporates the use of water retention layers and filter fabrics (Hydrotech Design), has 7.5 cm of growing media, and is comprised of various sedum species. Total event retention was compared for the 13 month study period associated with the traditional extensive green roof and the 12 month study period associated with the modular green roof blocks. These two studies were conducted at different times so only five storms overlapped and could be directly compared.. Because peak flow analysis for the traditional roof had been analyzed in units of flow rate (L/s), and data collected for the modular green roof blocks was collected at one minute intervals, comparisons were not made between the two green roofs.

Modeling

After measured values have been analyzed, an attempt was made to simulate values collected for the vegetated treatment using a process-based model constructed with Stella 8.1 modeling software. Stella 8.1 is a software package where the model can be visually constructed by developing flow diagrams and defining relationships among the flows.

Structure

Model structure is confined by the mass balance equation:

$$\text{Inputs} = \text{Outputs} + \Delta\ \text{Storage}$$

The basic flow within the model follows the format of Figure 3.11. The input for the model is precipitation and outputs for the model are evaporation, transpiration and runoff (water leached). The change in storage is the water contained by the block. Precipitation data was taken from two rain gauges located on the rooftop. To calculate the potential evapotranspiration, the Thornthwaite method was used, which is:

$$ET = 1.6 \, (10 \, Tm / I)^{a}$$

where	ET	potential evapotranspiration
	Tm	mean monthly temperature
	I	annual heat index
	^{a}	coefficient derived using (I)

This is an empirical equation that uses average monthly temperature as an index for the amount of energy available for evapotranspiration (Dunne and Leopold 1978). The actual rate is dependent upon the amount of water in the block available for evapotranspiration. There is also a correction factor associated with this formula that adjusts the rate for hours of sunlight in a day. This correction factor value can be obtained from a chart and is a function of latitude and time of year. The runoff rate will then be dependent upon the volumetric water content contained in the block. Once the volume of water in the block has exceeded the storage available (field capacity), runoff will occur.

Storage Determination

To determine the volume of water that a modular green roof block could retain, a short lab experiment was needed. A modular green roof block, filled with approximately 10 cm of engineered soil and no vegetation, was saturated to field capacity with a water hose. The block was then allowed to rest until no observable runoff was exiting the drain holes. The block was then weighed and compared to the weight of an empty block so the weight of the soil and the water could be determined. The soil was then dried in an oven, at forty degrees Celsius, for twenty-four hours and weighed again. By subtracting the field capacity weight by the dry weight, the weight of the water retained by the modular green roof block could be determined. This weight was then converted to a volume based on the assumption that one gram of water was equal to one cubic centimeter of water.

Simulated Runoff

Once the maximum field capacity or storage was determined, a few assumptions were needed to simulate runoff from the modular green roof blocks: 1) After a runoff event, the block is at field capacity, meaning the volume of water in the block is equal to the maximum water holding capacity; 2) Runoff from a modular green roof block does not occur until field capacity is reached, meaning the storage has been exceeded. With these two assumptions, a runoff equation was developed that took the form:

IF - Volume of Water < Field Capacity = No runoff occurs

IF - Volume of Water > Field Capacity = Runoff occurs

Using this equation, the model was constructed (Figure 3.12) and the hydraulic response was simulated for three months (November, February, and June). Simulations ran on an hourly timestep and began at the end of the first runoff event of the month, when the storage in the block could be assummed to be at field capacity. Simulated values were then compared to measured values using percent difference to determine the validity of the model. All model parameters, including values or formulas, are included in Table (3.1).

Table 3.1: List of model inputs and a description on how they were determined

Precipitation	Determined from raingauge data
Potential Evapotranspiration	Thornthwaite Equation
Average Monthly Temperature:	Determined from average monthly temperature over the last 60 years
Annual Heat Index:	Determined from average annual temperature
Coefficient (a):	Determined from the annual heat index
Correction Factor:	Determined from a chart based on latitude and time of year
Actual Evaportranspiration	=Potential Evapotranspiration X Soil Moisture
Runoff	Storage < Field Capacity = No runoff occurs Storage > Field Capacity = Runoff occurs
Storage	Inputs - Outputs
Water holding capacity	12.3 Liters- Determined from storage experiment
Soil Moisture	Storage / Water holding capacity
Total Area	Square footage of rooftop / 4 square feet

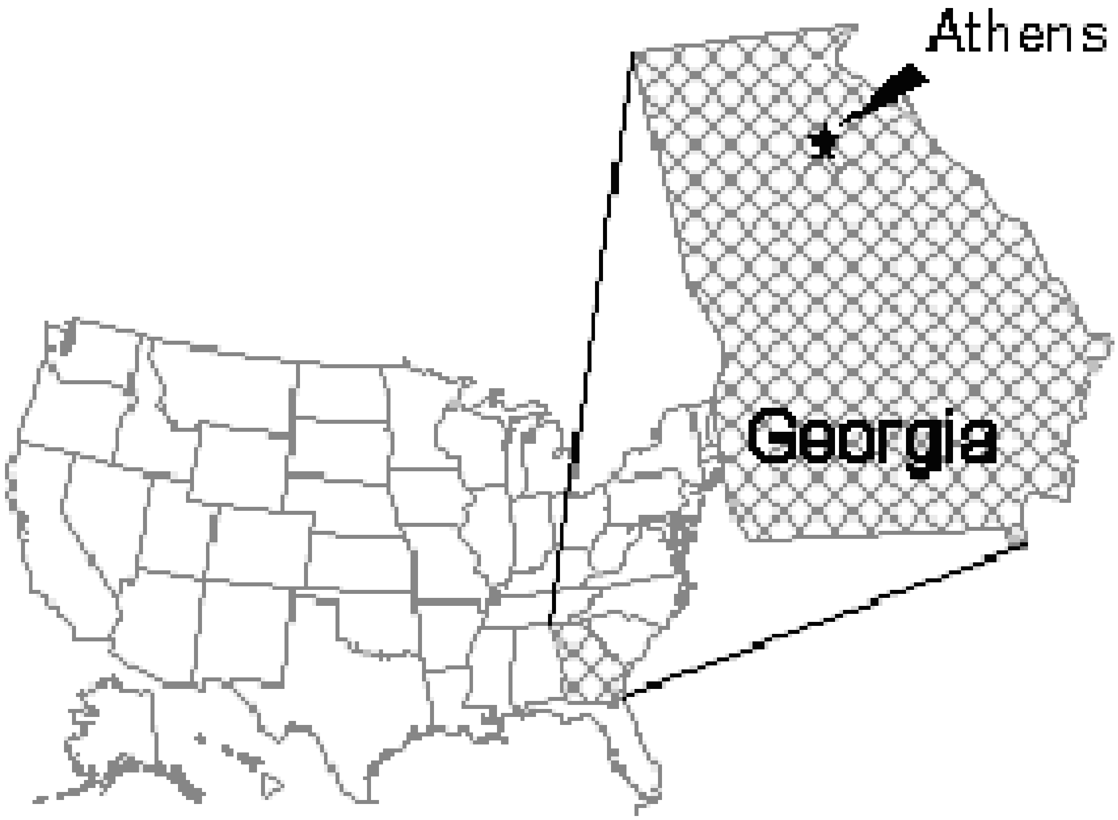

Figure 3.1: Location map for Athens, Georgia

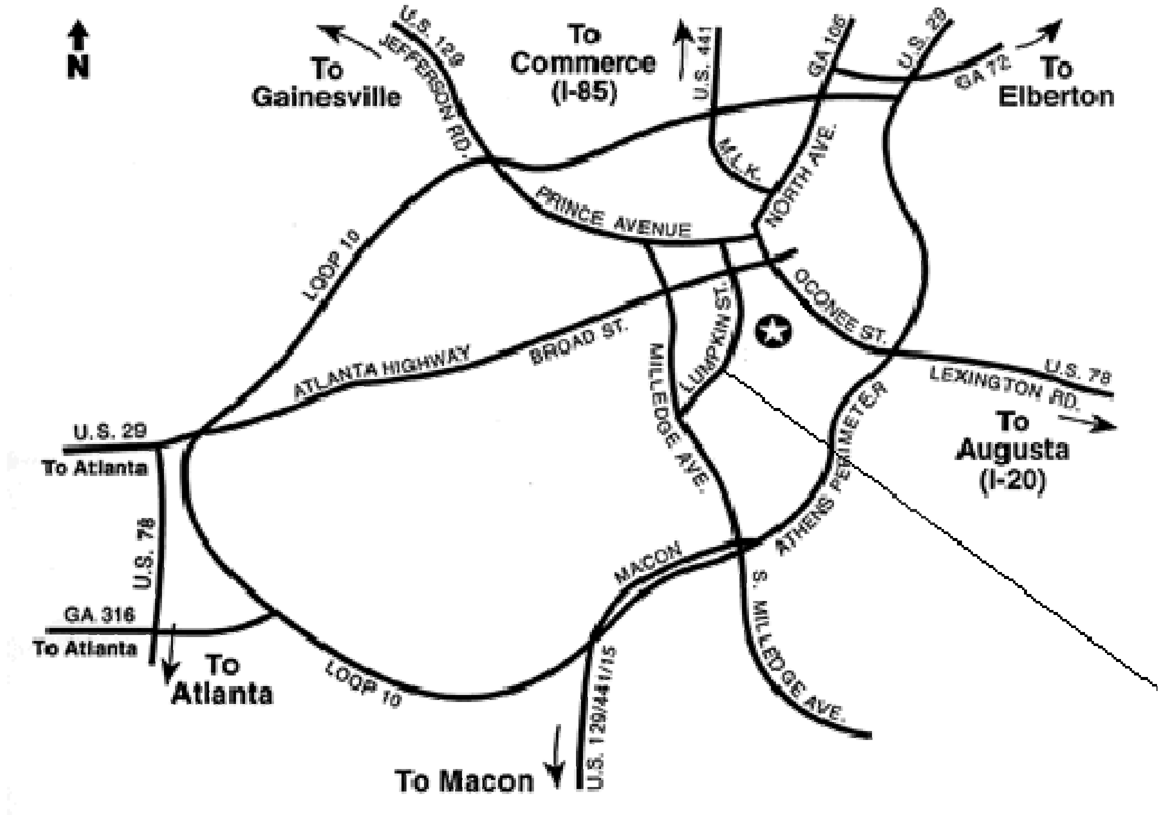

Figure 3.2: Location map for the study site

Figure 3.3: Picture of the study site

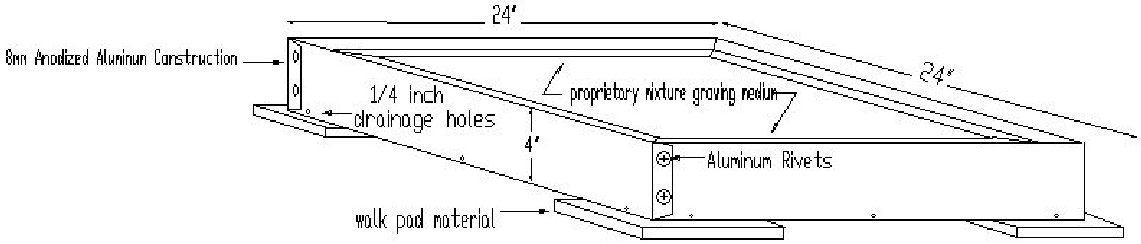

Figure 3.4: Schematic of a modular green roof block

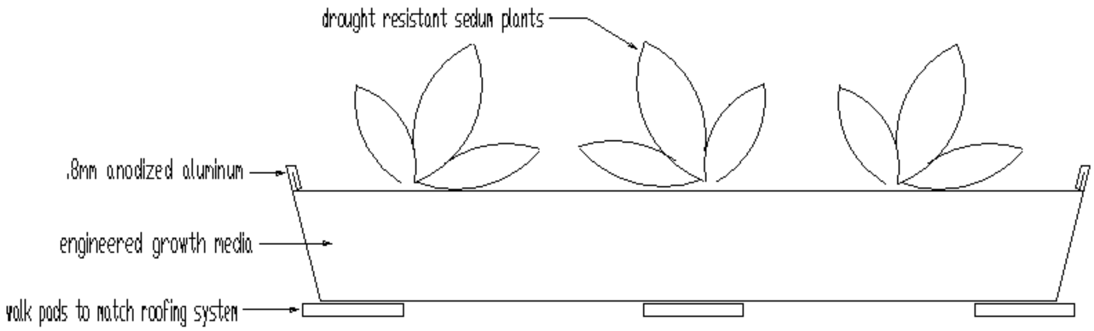

Figure 3.5: Schematic of a modular green roof block including vegetation

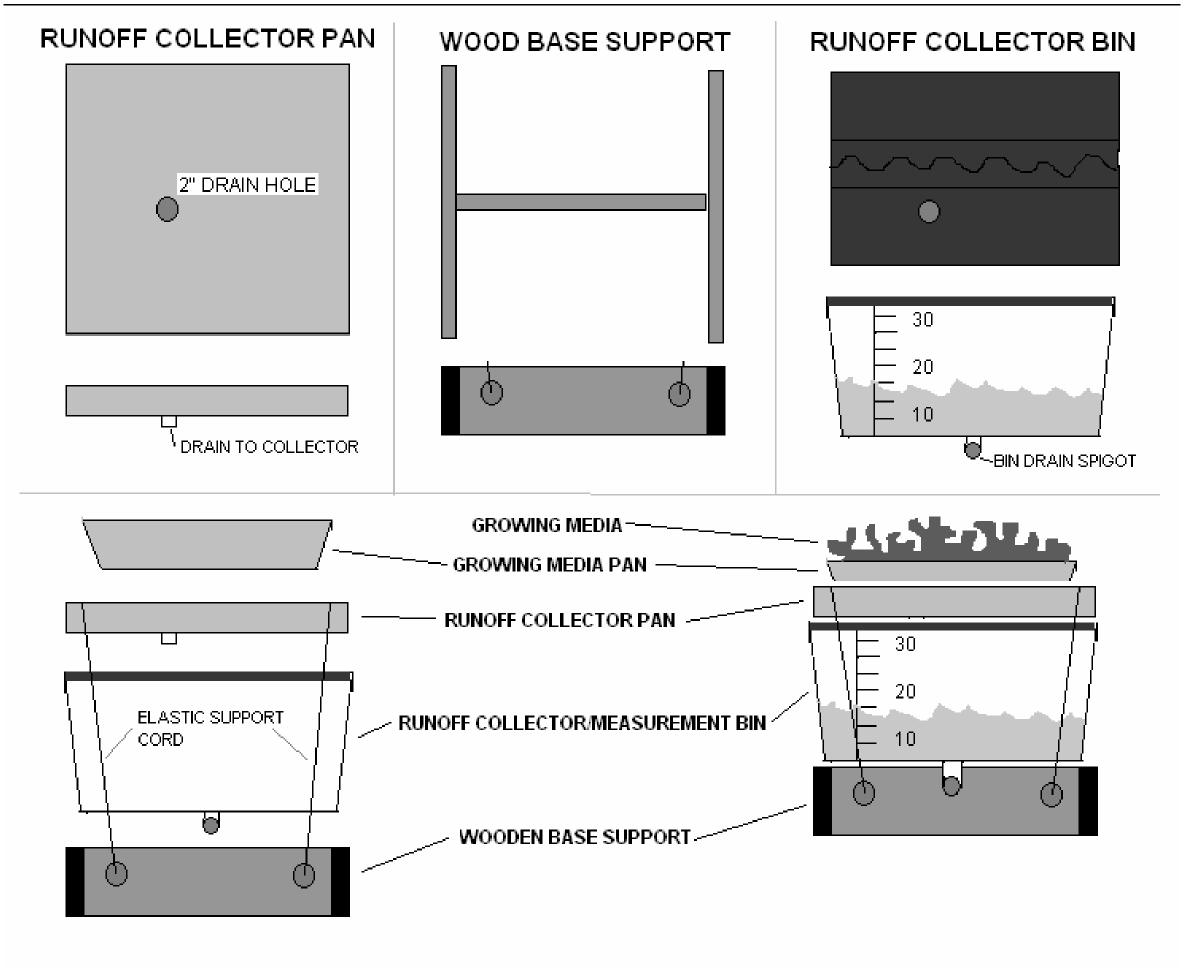

Figure 3.6: Schematic of the runoff collection design

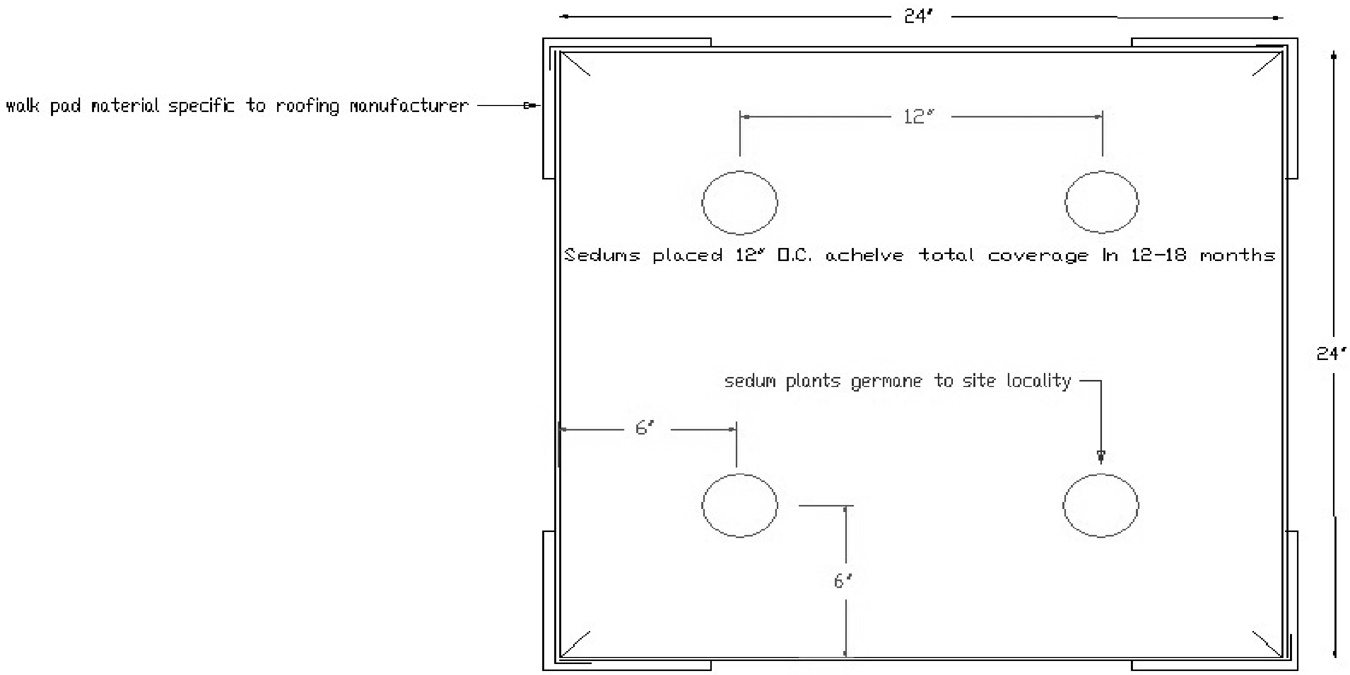

Figure 3.7: Schematic of planting location of sedum vegetation

Figure 3.8: Pictures of the three treatments

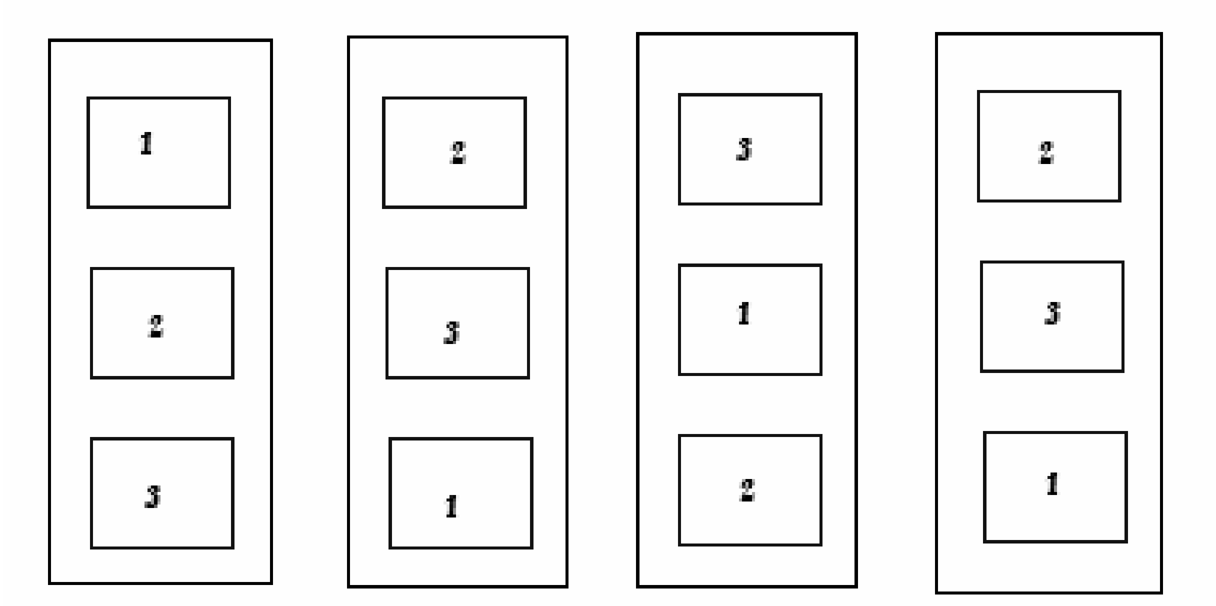

Figure 3.9: Illustration of randomized complete block design

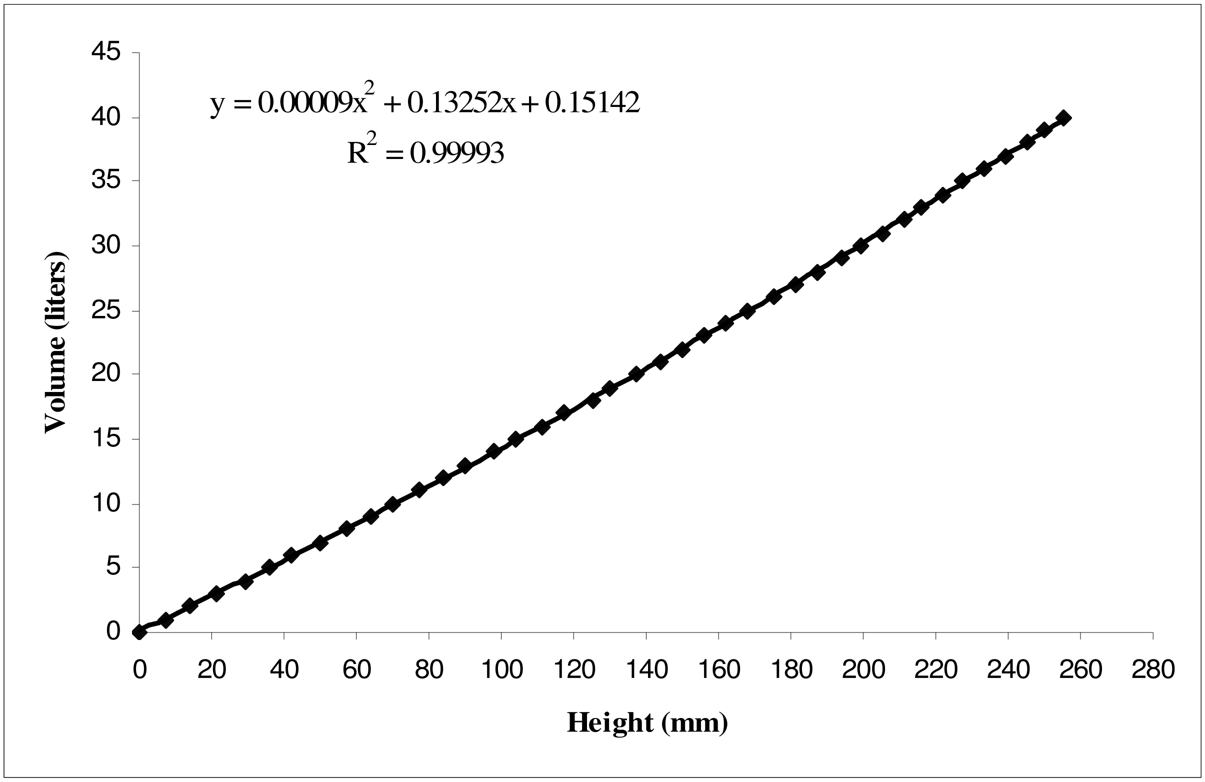

Figure 3.10: Water depth to volume conversion

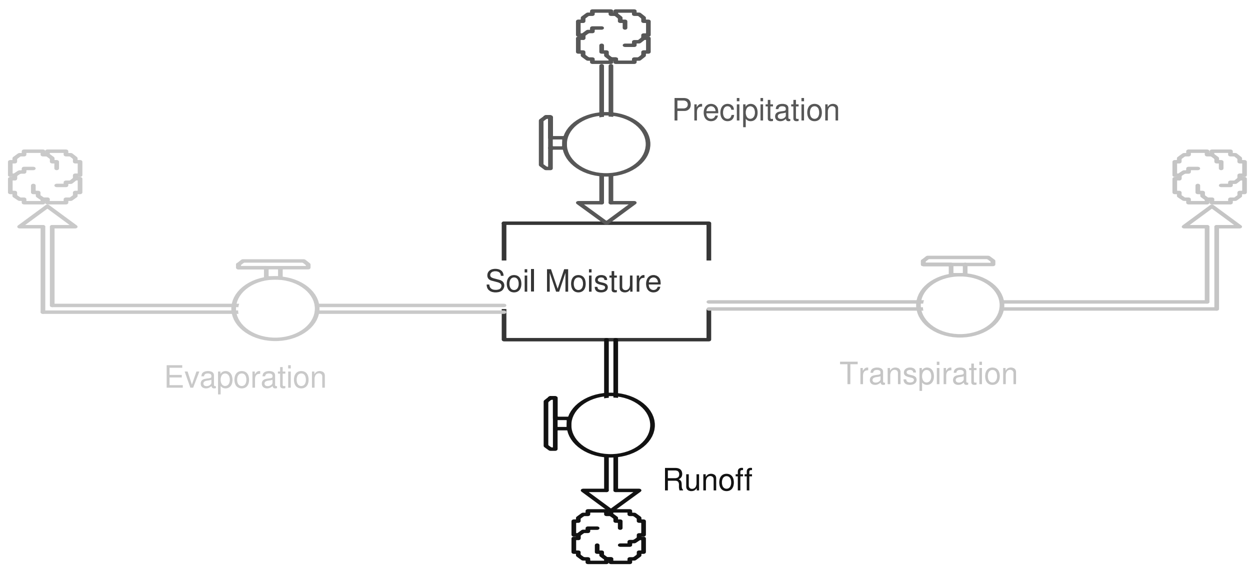

Figure 3.11: Diagram representing the flow within the model. The input is precipitation, the outputs are evaporation, transpiration, and runoff, and the change in storage is soil moisture contained within the block.

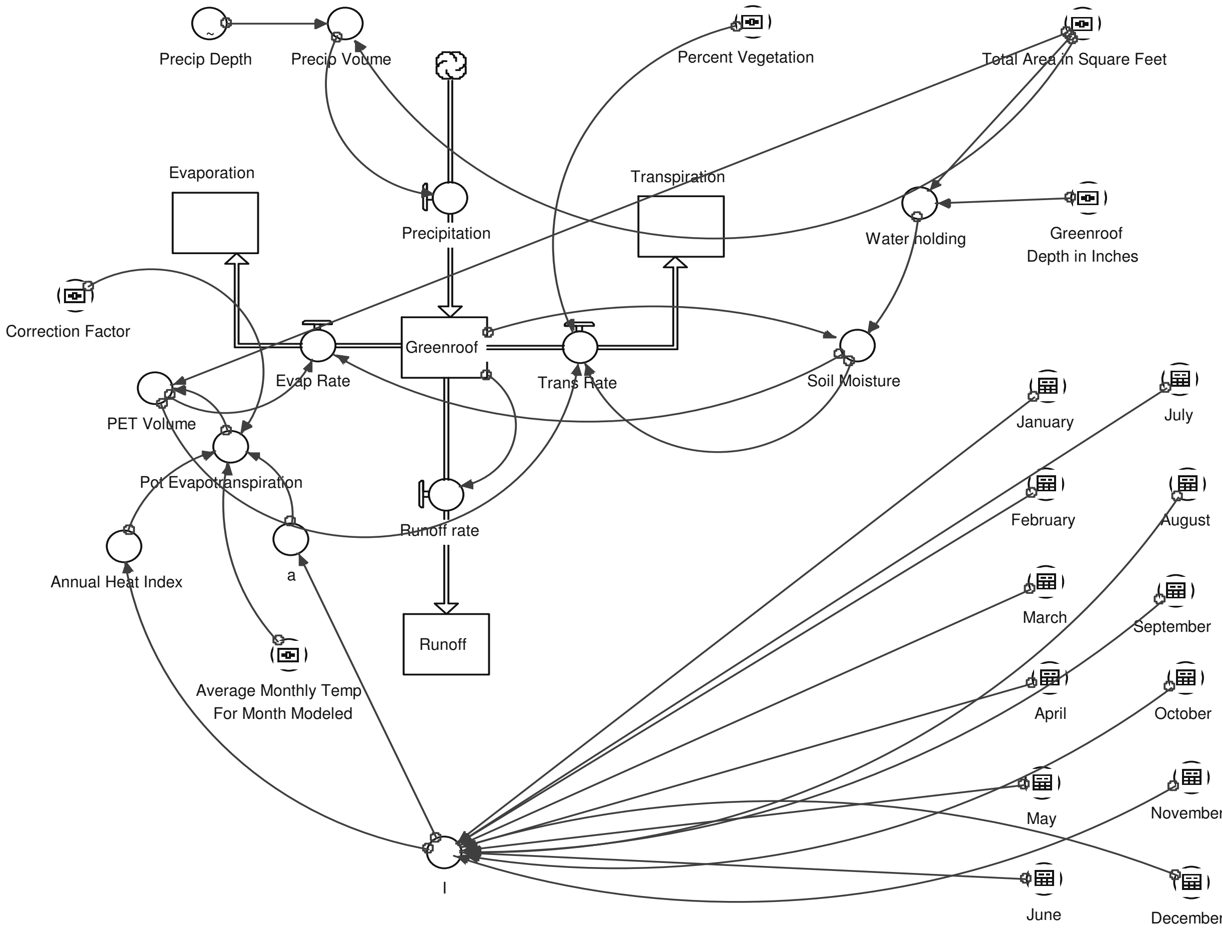

Figure 3.12: Structural interface of the model. This shows the flows within the model and the relationships between the flows. All model parameters can be manipulated at this location.

CHAPTER 4

RESULTS

Storm Events

Seventy storm events were recorded during the one-year study period from October 1, 2004, to September 30, 2005. Total annual rainfall measured 1,403 mm, approximately 150 mm above the average annual precipitation for Athens, Georgia. Figure 4.1 shows mean monthly precipitation in Athens and the observed monthly precipitation during the study period. Measurable precipitation was recorded on 136 out of 365 days, or 37%. Daily precipitation ranged from 0.254 mm to almost 93 mm (Figure 4.2). Precipitation amounts for the separate storm events (divided based on 24 consecutive hours of no rainfall) ranged from 0.254 mm to 117 mm during the 365-day study. The mean precipitation depth was 20.4 mm and the median precipitation depth was 13.2 mm. Of the 70 events measured, there were 23 light (<6 mm), 24 medium (6-25 mm), and 23 heavy (>25 mm) (Table 4.1).

Stormwater Retention

The vegetated and non-vegetated treatments displayed consistent results for all events. Vegetated and non-vegetated treatments retained precipitation until a field capacity point was reached, after which, runoff closely mimicked that of the reference treatment. Figure 4.3 shows average retention of all treatments for light, medium, and heavy storms. Notice that the vegetated and non-vegetated treatments retained almost all the precipitation during the light events, but less than 40% of the heavy storms. Throughout the year the vegetated and non-vegetated treatment retained between 42% and 44% or approximately 600 mm of the 1,403 mm of precipitation, while the reference treatment only retained approximately 2% or 28 mm. Mean retention of precipitation for the vegetated and non-vegetated treatments ranged from approximately 15 to 100% with an average retention for separate events of between 65% and 70%. The lower overall retention of precipitation (42%-44%) can be attributed to the distribution of rainfall. During the one year study, the 23 heavy precipitation events (33 % of total precipitation events) contributed to more than 73% of the total annual precipitation.

Observations showed that greater than approximately 0.51 mm of rainfall was required for runoff in the reference treatment to be generated. Even though the drain holes were located approximately 1 cm from the bottom, the slope in the blocks was probably accountable for the runoff at .51 mm. The smallest precipitation event for which runoff was recorded in the reference, non-vegetated, and vegetated treatments was 1.02 mm, 3.30 mm, and 4.57 mm, respectively. The largest precipitation event for which no runoff was recorded in the reference, non-vegetated, and vegetated treatments was .51 mm, 9.40, and 9.40, respectively. Of the 70 observed events, runoff was observed for 59 events for the reference, 45 events for the non-vegetated treatment, and 44 events for the vegetated treatment (Tables 4.3 – 4.5).

Tables 4.3 – 4.5 show all the precipitation events, including runoff depths for the three treatments; these tables are divided into heavy events, medium events, and light events. Note that for the light precipitation events, runoff occurred from the non-vegetated on only three occasions and from the vegetated treatment on only two occasions. The most storage provided by the vegetated treatment was for the fifth largest storm of the study, where 3.17 cm (11.81 Liters), 51% of the precipitation, was stored over the course of the event (Table 4.6). The smallest storage for the vegetated treatment occurred for the second smallest event in which .17 cm (.64 Liters), 38% of the precipitation was stored over the course of the event (Table 4.6). Figure 4.4 demonstrates the relationship between retention depth and precipitation depth provided by the three treatments during the one year study. From this graph, it is noticeable that the vegetated and non-vegetated treatment do not provide much retention after the first 4 cm of precipitation. Notice, when following the best fit trendline, that at 4 cm of rainfall, retention is approaching around1.60 cm, but at 12 cm of rainfall, retention only increases to 2.10 cm.

Retention percentage of the three treatments was negatively correlated with precipitation depth. Figure 4.5 shows that as precipitation depth increases the percent retention decreases. Notice that the trendlines for the vegetated and non-vegetated treatments are barely distinguishable while the reference treatment provided very little retention, especially after the first centimeter of rainfall. Note that Figure 4.4 displays the same data as Figure 4.5, but as retention depth as opposed to percentage.

Vegetated Treatment versus Reference Treatment

Results for the repeated measures ANOVA, with blocking, showed there was a statistically significant block effect and also a statistically significant treatment effect. The time, time × treatment interaction, and time × block interaction were also statistically significant, which was to be expected due to the temporal and spatial precipitation differences. To determine which treatments differed, Tukey's test was used. This test revealed that for all but one of the 44 events analyzed, runoff volumes for the vegetated treatment were reduced significantly when statistically compared to reference treatment. Refer to Table 4.7 for the ANOVA table that presents the associated 'F-scores' and 'degrees of freedom'.

Figure 4.6 presents data for the 59 events from which runoff was at least observed from the reference treatment. The data represents mean percent reduction provided by the vegetated treatment when compared to the reference treatment. The dot signifies the mean percent reduction and the error bars denote the maximum and minimum values associated with the vegetated treatment. It is apparent which event was not statistically significant. This particular event occurred in December of 2004 approximately 30 hours after the largest storm associated with the medium size events. This demonstrates one of the difficulties with storm event separation, especially when trying to compare events.

Vegetated Treatment versus Non-Vegetated Treatment

As mentioned above, results for the repeated measures ANOVA, with blocking, showed there was a statistically significant treatment effect. A Tukey's test showed that out of the 44 events analyzed, 36 of them were significantly different. For 21 of the 36 events, the test showed that the vegetated treatment had a significantly reduced volume of runoff, and for the other 15 events, the non-vegetated treatment had a significantly reduced volume of runoff. For 8 of the 44 events, the two treatments were not significantly different. Refer to Table 4.7 for the ANOVA table that presents the associated 'F-scores' and 'degrees of freedom'.

Even though the two treatments showed a statistical significant difference for 36 of the 44 events, because this difference went in both directions, the treatment effect, for all intensive purposes, is similar. Figure 4.7 demonstrates the mean percent reduction provided by the vegetated treatment when compared to the non-vegetated treatment. It is evident that for many of the events, the non-vegetated treatment actually retained more water than the vegetated treatment. None the less, the errors bars demonstrate the degree of variation associated with the treatments. It should be noted that for all but 5 of the 44 events, the error bars encompass zero. This suggests that the vegetated treatment and the non-vegetated treatment retained equal amounts of water throughout the course of the one year study. It should be noted that the one event far displaced from the others represents an event where runoff was generated in one of the non-vegetated treatment, but none of the vegetated treatments, creating large percent reductions.

Stormwater Detention

One of the primary strategies in stormwater management is providing detention for stormwater runoff. This involves retaining the ‘first flush’ of runoff that usually carries the majority of pollutants, reducing peak discharges, and releasing the peak discharges over a longer period. Figure 4.8 is a runoff hydrograph of a representative storm. This figure demonstrates the performance of the three treatments illustrating the initial abstraction, peak discharge attenuation, and runoff prolongation provided by non-vegetated and vegetated treatments.

Stormwater detention characteristics for the three treatments were analyzed for three months (October, February, June). Over these three months, 21 precipitation events occurred: 7 in October, 6 in February, and 8 in June. Of these 21 events, runoff from all three treatments was observed for 15 of these events: 1 in October, 6 in February, and 8 in June. Detention characteristics were analyzed for these 15 events and presented using notch-box plots. A box plot is a type of graph which is used to show the shape of the distribution, its central value, and spread (Tukey 1977). They are very useful when comparing data sets, determining whether a distribution is skewed, and/or whether there are any unusual observations. These plots consist of the most extreme values in the data set (maximum and minimum values), the lower and upper quartiles, and the median.

Initial Abstraction

In order to again clarify initial abstraction, for the purposes of this study it was defined as the depth of precipitation that had occurred when runoff was initiated in the representative treatment. Initial abstraction (IA) was provided by all treatments for all 15 storms analyzed for detention characteristics. Figure 4.9 shows IA provided by the three treatments. Notice that the median depth (cm) for the reference, non-vegetated and vegetated treatments were .05, .36, and .38, respectively, for the three periods. The vegetated and non-vegetated treatments displayed very similar depths across storms and were much more variable than the reference treatment, which was to be expected.

Peak Discharge Attenuation

For the purposes of this study, peak discharge attenuation was defined as the reduction in peak runoff measured in the non-vegetated and vegetated treatments relative to the reference treatment. Peak discharge attenuation was provided for most storms during the three periods analyzed. Figure 4.10 shows peak discharge attenuation provided by the non-vegetated and vegetated treatments. This graph demonstrates the median attenuations (cm/min) for the non-vegetated and vegetated treatments, relative to the reference, which were $3.36\ E^{-3}$ and $5.34\ E^{-3}$, respectively, for the three periods. Notice how the whiskers on the box plots are longer on the top than the bottom. This demonstrates the skewed distribution of values seen for peak discharge attenuation. Although there were some large values, 75% of the values were contained within the top of the box. It should also be noted that for one event, the non-vegetated treatment actually had a larger peak discharge than did the reference treatment.

Runoff Prolongation

Runoff prolongation, for this study, was defined as the time the runoff hydrograph was extended by the representative treatment relative to the senescence of rainfall. Runoff prolongation was generally provided by the three treatments. This data is presented in Figure 4.11. Notice that the median prolongation times for the reference, non-vegetated and vegetated, relative to the senescence of rainfall, were 18, 32, and 36 minutes, respectively, for the three periods. Although the large prolongation times were expected for the non-vegetated and vegetated treatments, it was surprising that the reference treatment had a median prolongation of 18 minutes. Also notice that the reference treatment had a negative time for the minimum value in the data set. Although there is no such thing as negative time, this represents that precipitation continued even after runoff from the reference treatment had terminated. This could either demonstrate un-uniform rain patterns or equipment malfunction, but regardless it portrays the difficulties with monitoring in real-time.

Modular Green Roof Blocks versus Traditional Extensive Green Roof

One of the primary objectives of this research was to determine the ability of modular green roof blocks to retain and detain stormwater relative to traditional green roofs. Because of the difficulties in comparing runoff characteristics spatially and temporally, it was necessary that comparisons be made for equivalent storm events under the same climatic conditions. Fortunately, adjacent to the study site location, there is a traditional green roof for which these comparisons can be made. This traditional green roof is located on the same roof, so meteorological conditions are comparable across sites. Total event retention was compared between the two different green roof types for five storms during October and November of 2004.

Table 4.11 presents the rainfall, runoff, and percent difference between the two roofs for the five referenced events. The traditional green roof reduced runoff an average of 80% for the five storms where as the modular green roof blocks reduced runoff an average of 60%. The traditional green roof, on average, provided approximately 20% more retention. For the smallest event, the modular green roof blocks provided more retention than the traditional green roof; 100% versus 90%. This could be due to the difference in sensitivity between monitoring equipment.

To compare the two roofs across a larger data set, event storage as a function of precipitation depth was compared (Figure 4.16). It is evident that the traditional extensive roof was able to store more water, relative to precipitation depth, for the events it experienced. It should be noted that only five of these events overlapped, so antecedent moisture conditions were not comparable, even during events of equal precipitation depth. It should also be restated that above average rainfall occurred during the twelve month study of the modular green roof blocks, 32 cm more than during the thirteen month study of the traditional extensive roof. So considering the meteorological differences the roofs experienced, comparing these two data sets might be misleading. However, the traditional extensive green roof allowed for 20% more storage, which is consistent with the results above that compared the same five storms events.

Modeling

Storage Determination

When the modular green roof block was saturated and excess water had drained, the soil weighed approximately 37,875 grams. After the soil was oven dried, it weighed 25,558 grams. The difference between these two weights, 12,317 grams, was then the weight of the water held by the soil. Using the conversion 1 gram of water equals 1 cubic cm of water, it was determined that the maximum field capacity of the modular green roof block was 12, 317 mL or 12.3 Liters of water. With this information the runoff equation now looks like:

IF - Volume of Water ≤ 12.3 Liters = No runoff occurs

IF - Volume of Water > 12.3 Liters = Runoff occurs

Simulation Results

Results showed that the model performed adequately during simulations. Figure 4.17 demonstrates measured and simulated values during a representive storm. In comparing the simulated and measured values, the overall retention for a storm event was similar, although simulated values consistently delayed runoff longer than the measured values. Figure 4.18 shows the mean percent difference of total event runoff between the simulated and measured values for the 18 modeled events. The error bars represent the maximum and minimum of the vegetated treatment, while the dot represents the mean. Of these 18 events, only two of them showed greater than a 10% mean difference between the simulated and measured values.

Table 4.1: List of 70 recorded events during the one year study. They are divided into Heavy, Medium, and Light based on precipitation depth.

Heavy Storms		**Medium Storms**		**Light Storms**	
Date	Depth (mm)	Date	Depth (mm)	Date	Depth(mm)
11/21/2004	117.35	12/9/2004	22.35	8/29/2005	4.83
7/6/2005	84.07	6/8/2005	22.10	11/27/2004	4.57
6/18/2005	65.79	2/23/2005	21.59	1/6/2005	3.56
4/7/2005	64.26	6/27/2005	20.57	3/14/2005	3.30
2/20/2005	61.72	7/28/2005	19.81	7/15/2005	3.05
3/27/2005	61.47	12/5/2004	19.56	12/10/2004	2.03
1/13/2005	59.18	3/7/2005	19.05	4/28/2005	2.03
5/31/2005	58.17	3/16/2005	17.53	10/14/2004	1.78
3/31/2005	54.36	6/11/2005	15.75	10/24/2004	1.78
11/2/2004	38.35	10/19/2004	14.99	8/18/2005	1.52
5/14/2005	37.85	6/20/2005	13.97	10/3/2004	1.02
12/22/2004	35.05	2/27/2005	13.46	8/5/2005	1.02
6/30/2005	34.80	4/22/2005	12.95	11/19/2004	0.51
7/10/2005	32.00	2/14/2005	12.45	1/22/2005	0.51
2/2/2005	30.23	11/4/2004	12.19	7/19/2005	0.51
7/21/2005	28.19	2/8/2005	11.68	8/16/2005	0.51
8/7/2005	27.18	10/12/2004	9.40	10/9/2004	0.25
6/29/2005	25.40	12/1/2004	8.89	10/22/2004	0.25
11/11/2004	25.15	4/26/2005	8.64	1/7/2005	0.25
4/30/2005	24.89	5/20/2005	8.38	1/9/2005	0.25
4/12/2005	24.38	6/25/2005	7.87	8/11/2005	0.25
3/21/2005	23.88	7/3/2005	7.62	8/13/2005	0.25
5/29/2005	23.11	9/23/2005	5.84	8/25/2005	0.25
		1/30/2005	5.33		

Table 4.2: Percent retention of different size storms. Gives retention values for the three treatments that correspond with Figure 4.3

	Reference	Non-Vegetated	Vegetated
Heavy	1.09%	36.09%	36.76%
Medium	5.62%	56.69%	58.75%
Light	14.84%	83.48%	84.86%
Overall	2.50%	42.25%	43.14%

Table 4.3.: Heavy Precipitation Events (mm). Shows the runoff depth from the three treatments.

Date	Precipitation	Control	Non-Vegetated	Vegetated
11/21/2004	117.35	119.56	96.28	95.90
7/6/2005	84.07	83.50	58.77	56.14
6/18/2005	65.79	66.74	47.11	47.31
4/7/2005	64.26	61.37	43.62	39.18
2/20/2005	61.72	59.24	30.97	29.95
3/27/2005	61.47	60.18	42.36	42.71
1/13/2005	59.18	56.24	37.38	37.61
5/31/2005	58.17	56.11	41.90	41.72
3/31/2005	54.36	53.52	27.73	31.91
11/2/2004	38.35	37.76	16.09	15.98
5/14/2005	37.85	40.36	26.93	26.11
12/22/2004	35.05	33.49	19.79	18.99
6/30/2005	34.80	34.56	24.53	24.63
7/10/2005	32.00	30.98	22.45	22.49
2/2/2005	30.23	32.50	22.25	22.86
7/21/2005	28.19	24.86	13.15	12.40
8/7/2005	27.18	29.15	14.27	13.78
6/29/2005	25.40	24.18	15.79	16.10
11/11/2004	25.15	24.50	13.89	13.94
4/30/2005	24.89	25.41	15.83	15.59
4/12/2005	24.38	25.37	13.36	12.85
3/21/2005	23.88	22.57	11.17	10.70
5/29/2005	23.11	23.37	7.06	6.86

Table 4.4: Medium Precipitation Events (mm). Shows the runoff depth from the three treatments.

Date	Precipitation	Control	Non-Vegetated	Vegetated
12/9/2004	22.35	22.28	15.49	16.12
6/8/2005	22.10	21.55	13.25	12.48
2/23/2005	21.59	20.87	15.79	14.57
6/27/2005	20.57	19.57	13.61	13.62
7/28/2005	19.81	18.38	5.91	5.68
12/5/2004	19.56	18.71	7.33	7.97
3/7/2005	19.05	15.45	8.89	8.44
3/16/2005	17.53	18.02	4.18	1.71
6/11/2005	15.75	14.80	7.87	7.46
10/19/2004	14.99	14.40	6.90	6.40
6/20/2005	13.97	13.07	8.99	9.45
2/27/2005	13.46	11.39	7.17	6.93
4/22/2005	12.95	12.95	3.18	3.43
2/14/2005	12.45	12.33	4.66	4.68
11/4/2004	12.19	13.00	7.22	7.07
2/8/2005	11.68	10.78	5.64	5.75
10/12/2004	9.40	9.97	0.00	0.00
12/1/2004	8.89	7.95	3.16	2.79
4/26/2005	8.64	7.13	0.00	0.00
5/20/2005	8.38	7.95	0.00	0.00
6/25/2005	7.87	7.17	1.82	1.56
7/3/2005	7.62	5.48	0.81	0.84
9/23/2005	5.84	5.27	0.00	0.00
1/30/2005	5.33	4.86	0.00	0.00

Table 4.5: Light Precipitation Events (mm). Shows the runoff depth from the three treatments.

Date	Precipitation	Control	Non-Vegetated	Vegetated
8/29/2005	4.83	4.11	0.00	0.00
11/27/2004	4.57	4.64	2.67	2.84
1/6/2005	3.56	3.51	0.00	0.00
3/14/2005	3.30	3.03	0.61	0.00
7/15/2005	3.05	2.79	0.00	0.00
12/10/2004	2.03	2.48	2.38	2.35
4/28/2005	2.03	2.52	0.00	0.00
10/14/2004	1.78	1.61	0.00	0.00
10/24/2004	1.78	1.54	0.00	0.00
8/18/2005	1.52	0.92	0.00	0.00
10/3/2004	1.02	1.23	0.00	0.00
8/5/2005	1.02	0.83	0.00	0.00
11/19/2004	0.51	0.00	0.00	0.00
1/22/2005	0.51	0.00	0.00	0.00
7/19/2005	0.51	0.00	0.00	0.00
8/16/2005	0.51	0.00	0.00	0.00
10/9/2004	0.25	0.00	0.00	0.00
10/22/2004	0.25	0.00	0.00	0.00
1/7/2005	0.25	0.00	0.00	0.00
1/9/2005	0.25	0.00	0.00	0.00
8/11/2005	0.25	0.00	0.00	0.00
8/13/2005	0.25	0.00	0.00	0.00
8/25/2005	0.25	0.00	0.00	0.00

Table 4.6: Retention percentage and storage volume provided by the vegetated treatment

Rainfall (mm)	Retention (%)	Storage (L)	Rainfall (mm)	Retention (%)	Storage (L)	Rainfall (mm)	Retention (%)	Storage (L)
117.35	18.28	7.97	22.35	27.87	2.31	4.83	100.00	1.79
84.07	33.23	10.38	22.10	43.52	3.57	4.57	37.86	0.64
65.79	28.09	6.87	21.59	32.50	2.61	3.56	100.00	1.32
64.26	39.03	9.32	20.57	33.81	2.59	3.30	91.42	1.22
61.72	51.48	11.81	19.81	71.35	5.25	3.05	100.00	1.13
61.47	30.52	6.97	19.56	59.26	4.31	2.03	*	*
59.18	36.45	8.02	19.05	55.70	3.94	2.03	100.00	0.76
58.17	28.28	6.11	17.53	90.22	5.88	1.78	100.00	0.66
54.36	41.29	8.34	15.75	52.63	3.08	1.78	100.00	0.66
38.35	58.33	8.31	14.99	57.29	3.19	1.52	100.00	0.57
37.85	31.00	4.36	13.97	32.34	1.68	1.02	100.00	0.38
35.05	45.83	5.97	13.46	48.50	2.43	1.02	100.00	0.38
34.80	29.23	3.78	12.95	73.49	3.54	0.51	100.00	0.19
32.00	29.72	3.53	12.45	62.38	2.88	0.51	100.00	0.19
30.23	24.36	2.74	12.19	42.04	1.90	0.51	100.00	0.19
28.19	56.02	5.87	11.68	50.79	2.21	0.51	100.00	0.19
27.18	49.28	4.98	9.40	100.00	3.49	0.25	100.00	0.09
25.40	36.61	3.46	8.89	68.66	2.27	0.25	100.00	0.09
25.15	44.57	4.17	8.64	100.00	3.21	0.25	100.00	0.09
24.89	37.37	3.46	8.38	100.00	3.11	0.25	100.00	0.09
24.38	47.32	4.29	7.87	80.24	2.35	0.25	100.00	0.09
23.88	55.20	4.90	7.62	89.03	2.52	0.25	100.00	0.09
23.11	70.32	6.04	5.84	100.00	2.17	0.25	100.00	0.09
			5.33	100.00	1.98			

* Represents one storm for which runoff from the vegetated treatment was actually larger than the precipitation depth measured.

Table 4.7: ANOVA tables associated with comparisons made within and among treatments.

Repeated Measures Analysis of Variance: Tests of Hypothesis for Between Subject Effects					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Treatment	2	1.92E+09	9.58E+08	Infty	<.0001
Block	3	3.78E+08	1.26E+08	Infty	<.0001
Error	4	0	0		

Repeated Measures Analysis of Variance: Tests of Hypothesis for Within Subject Effects					
Source	DF	ANOVA SS	Mean Square	F Value	Pr > F
Time	43	2.43E+10	5.65E+08	1590.01	<.0001
Time*Treatment	86	6.32E+08	7.34E+06	20.68	<.0001
Time*Block	129	2.11E+08	1.64E+06	4.6	<.0001
Error	172	6.11E+07	3.55E+05		

Table 4.8: Initial abstraction (cm) provided by the three treatments. This parameter was defined as the accumulated rainfall depth at the time runoff was generated.

Date	Rainfall (cm)	Reference	Non-Vegetated	Vegetated
10/19/2004	1.50	0.1016	0.381	0.4064
2/2/2005	3.02	0.0762	0.762	0.7874
2/8/2005	1.17	0.127	0.3048	0.4064
2/14/2005	1.24	0.0254	0.2032	0.254
2/20/2005	6.17	0.1016	0.2794	0.3302
2/23/2005	2.16	0.0508	0.4064	0.5588
2/27/2005	1.35	0.0508	0.3556	0.3556
6/8/2005	2.21	0.2794	0.9652	0.9652
6/11/2005	1.57	0.127	0.381	0.381
6/18/2005	6.58	0.0254	0.4572	0.4572
6/20/2005	1.40	0.127	0.1778	0.1778
6/25/2005	0.79	0.0508	0.2794	0.3302
6/27/2005	2.06	0.0508	0.508	0.508
6/29/2005	2.54	0.0254	0.1016	0.1016
6/30/2005	3.48	0.0254	0.1778	0.1778
Mean	2.48	0.08	0.38	0.41

Table 4.9: Peak discharge attenuation (cm/minute) provided by the non-vegetated and vegetated treatments relative to the reference treatment

Date	Rainfall (cm)	Non-Vegetated	Vegetated
10/19/2004	1.50	1.31E-03	7.80E-04
2/2/2005	3.02	5.85E-04	8.40E-03
2/8/2005	1.17	2.69E-03	2.34E-03
2/14/2005	1.24	8.71E-04	6.55E-04
2/20/2005	6.17	1.39E-03	1.10E-02
2/23/2005	2.16	5.23E-03	4.38E-03
2/27/2005	1.35	3.36E-03	3.71E-03
6/8/2005	2.21	1.13E-02	1.11E-02
6/11/2005	1.57	-3.78E-04	3.05E-04
6/18/2005	6.58	4.04E-02	3.65E-02
6/20/2005	1.40	1.39E-02	1.53E-02
6/25/2005	0.79	3.22E-03	3.45E-03
6/27/2005	2.06	4.96E-03	5.34E-03
6/29/2005	2.54	7.77E-03	7.30E-03
6/30/2005	3.48	7.57E-03	7.36E-03
Mean	2.48	7.E-03	8.E-03

Table 4.10: Runoff prolongation (minutes) provided by the three treatments relative to the senescence of precipitation

Date	Rainfall (cm)	Reference	Non-Vegetated	Vegetated
10/19/2004	1.50	18	22	28
2/2/2005	3.02	2	20	24
2/8/2005	1.17	32	70	88
2/14/2005	1.24	24	68	60
2/20/2005	6.17	16	88	92
2/23/2005	2.16	16	66	78
2/27/2005	1.35	-12	30	36
6/8/2005	2.21	38	52	58
6/11/2005	1.57	12	26	16
6/18/2005	6.58	4	26	32
6/20/2005	1.40	12	32	28
6/25/2005	0.79	36	46	38
6/27/2005	2.06	24	28	30
6/29/2005	2.54	18	22	20
6/30/2005	3.48	30	36	38
Mean	2.48	18	42	44

Table 4.11: Green Roof Blocks versus Traditional Green Roof. Presents the runoff depth (mm) for each of these green roofs for the five storm events where studies periods overlapped.

Date	Rainfall (mm)	Modular (mm)	Traditional (mm)	% Difference
10/12/2004	9.4	0.0	1.0	-10.6
10/19/2004	15.0	6.4	3.9	16.7
11/3/2004	38.4	16.0	8.2	20.3
11/4/2004	12.2	7.1	2.6	36.6
11/12/2004	25.1	13.9	4.5	37.5

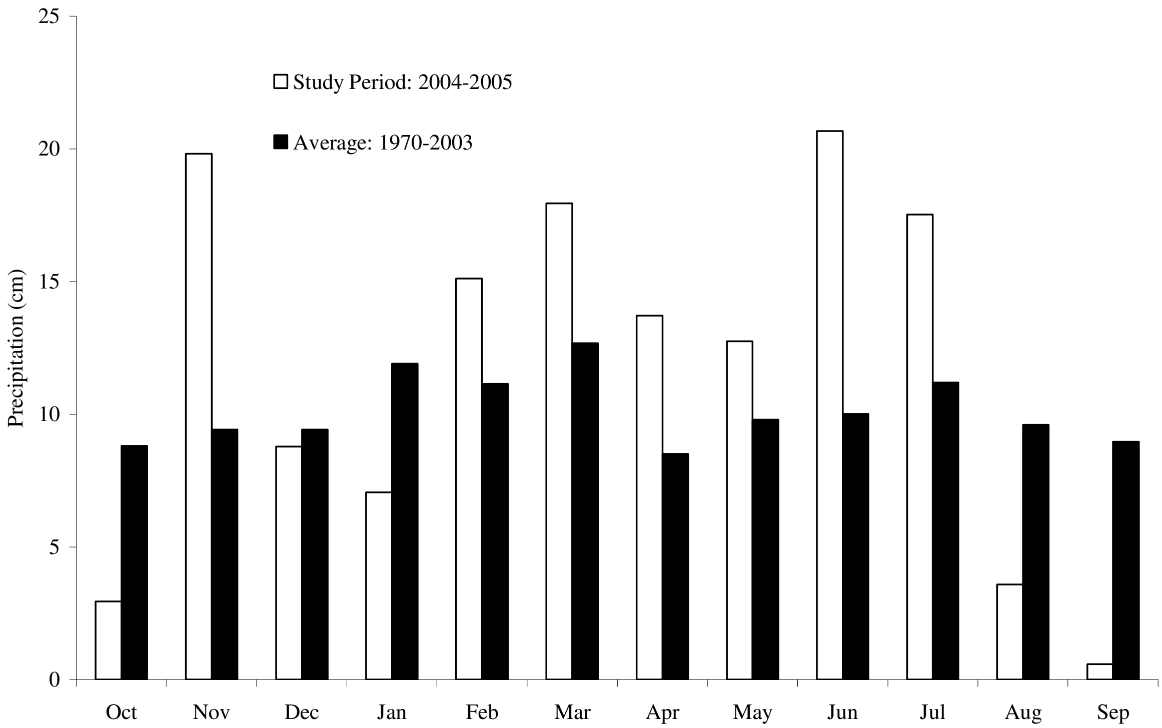

Figure 4.1: Comparison of average and study period monthly precipitation for Athens, Georgia

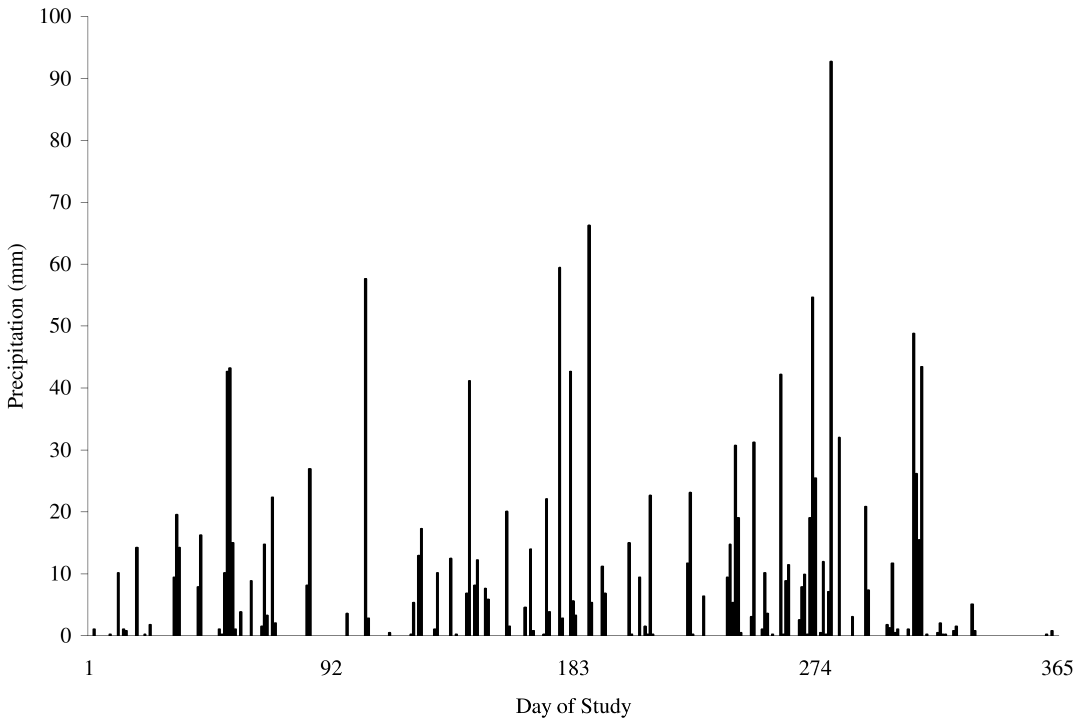

Figure 4.2: Daily precipitation during the one year study. The days of the study correspond with the day of the 2006 Water Year.

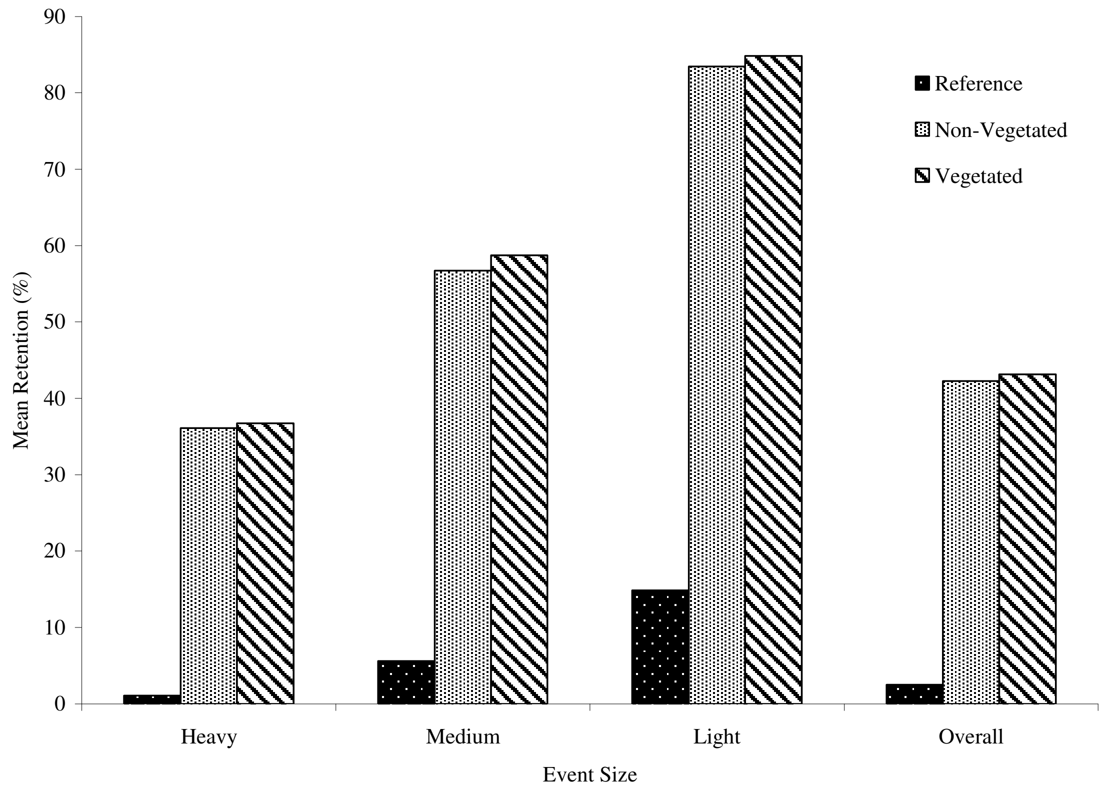

Figure 4.3: Percent retention for different size storms. Presents the mean percent retention for the three treatments for different size storms and for the overall study period

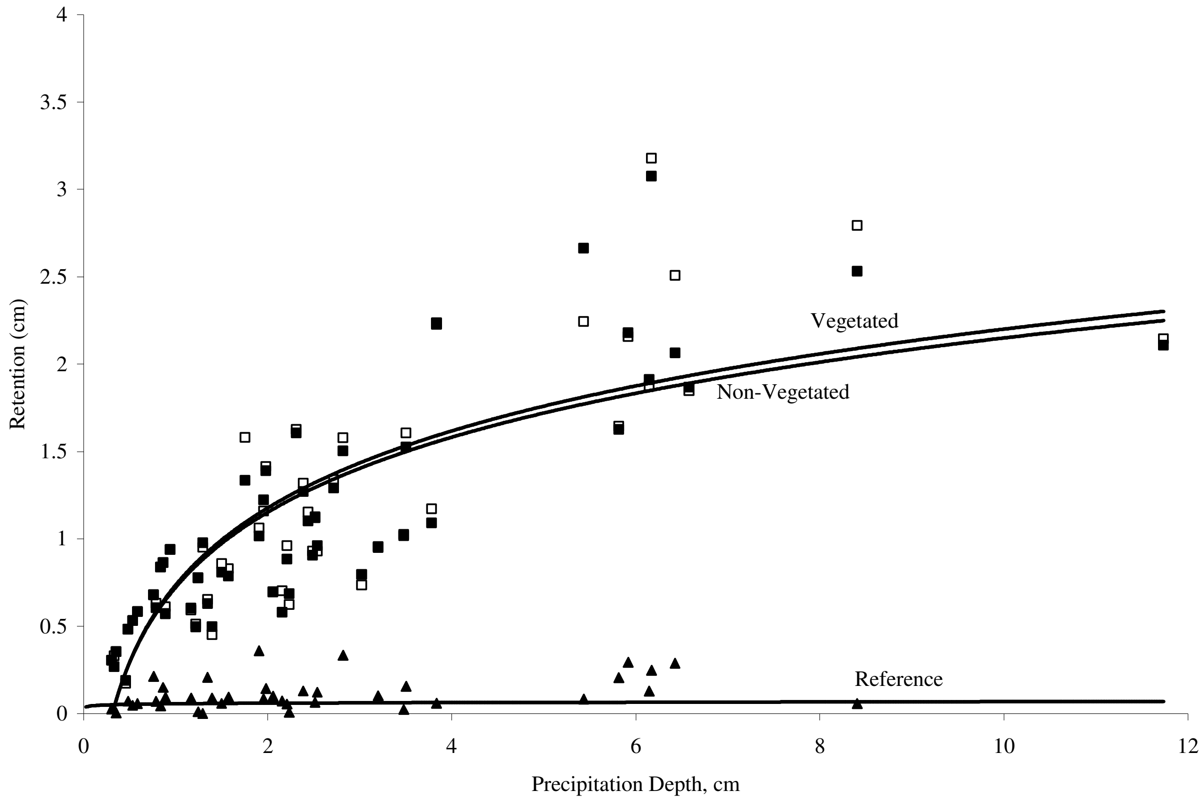

Figure 4.4: Retention depth of the three treatments as a function of precipitation depth. The open square represent the vegetated treatment, the solid square represent the non-vegetated treatment and the solid triangles represent the reference treatment.

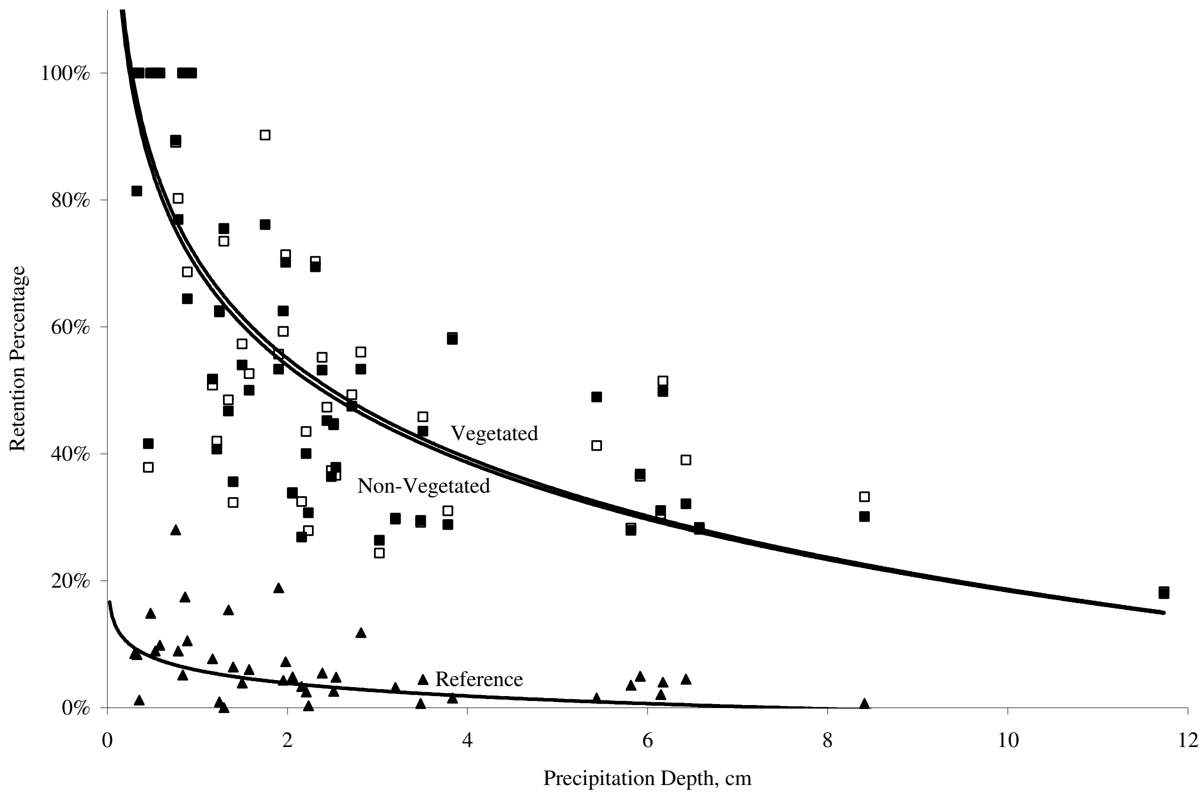

Figure 4.5: Retention percentage of the three treatments as a function of precipitation depth. The open square represent the vegetated treatment, the solid square represent the non-vegetated treatment and the solid triangles represent the reference treatment.

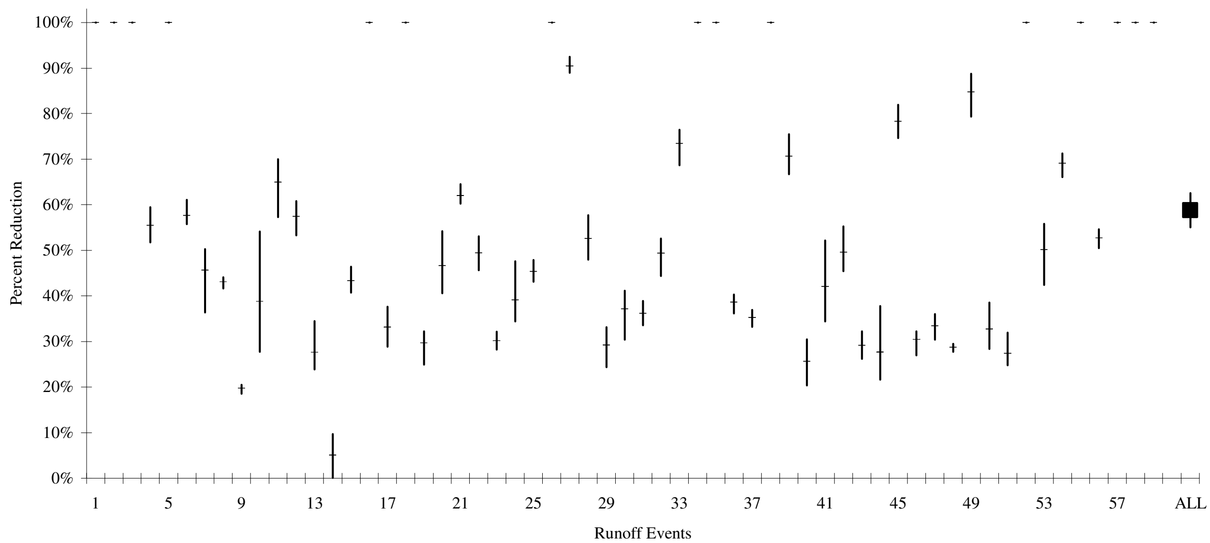

Figure 4.6: Percent runoff reduction provided by the vegetated treatment when compared to the reference treatment.

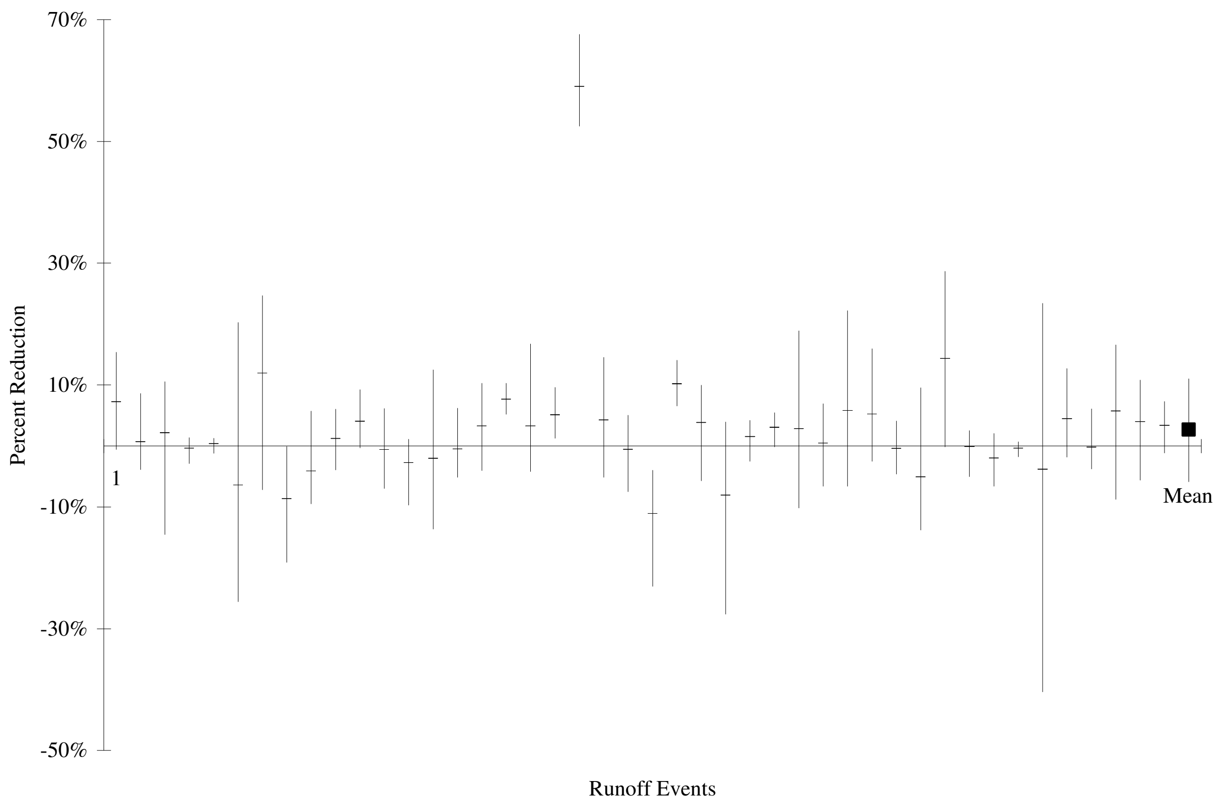

Figure 4.7: Percent runoff reduction provided by the vegetated treatment when compared to the non-vegetated treatment.

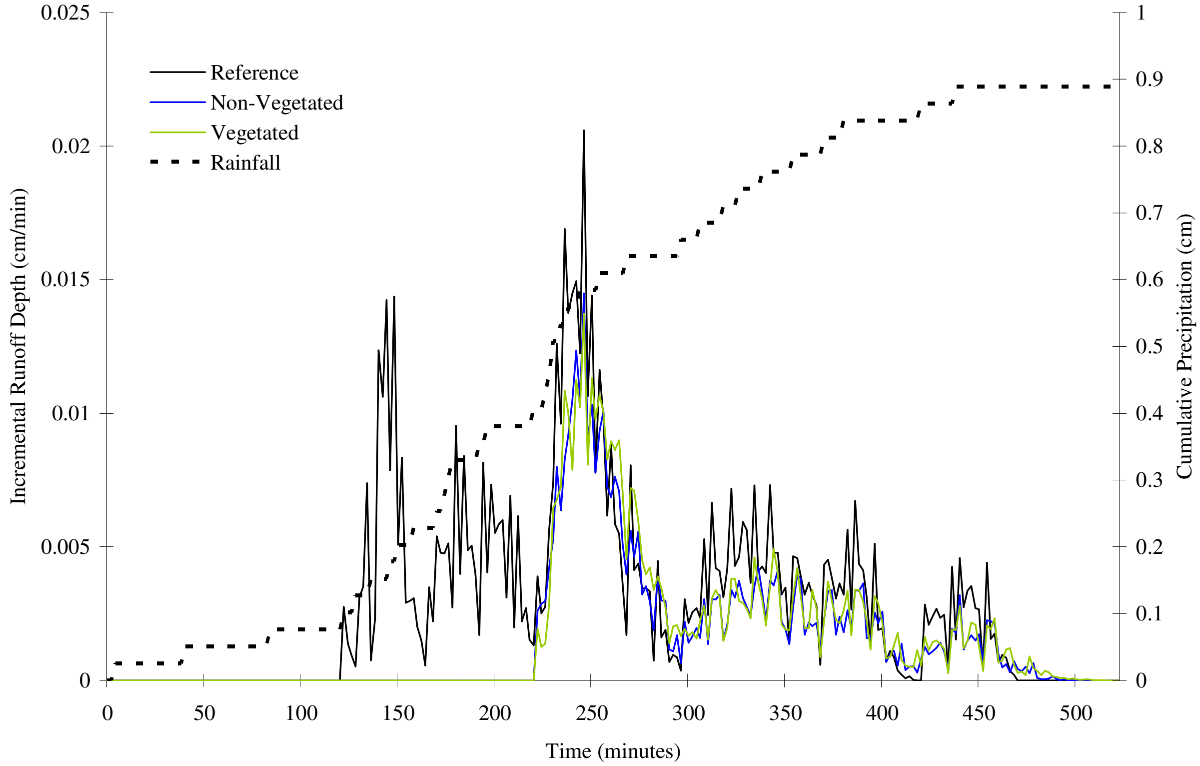

Figure 4.8: Runoff hydrograph of a representative storm. This graph demonstrates the performance of the three treatments, highlighting initial abstraction, peak discharge attenuation, and runoff prolongation, compared to cumulative precipitation.

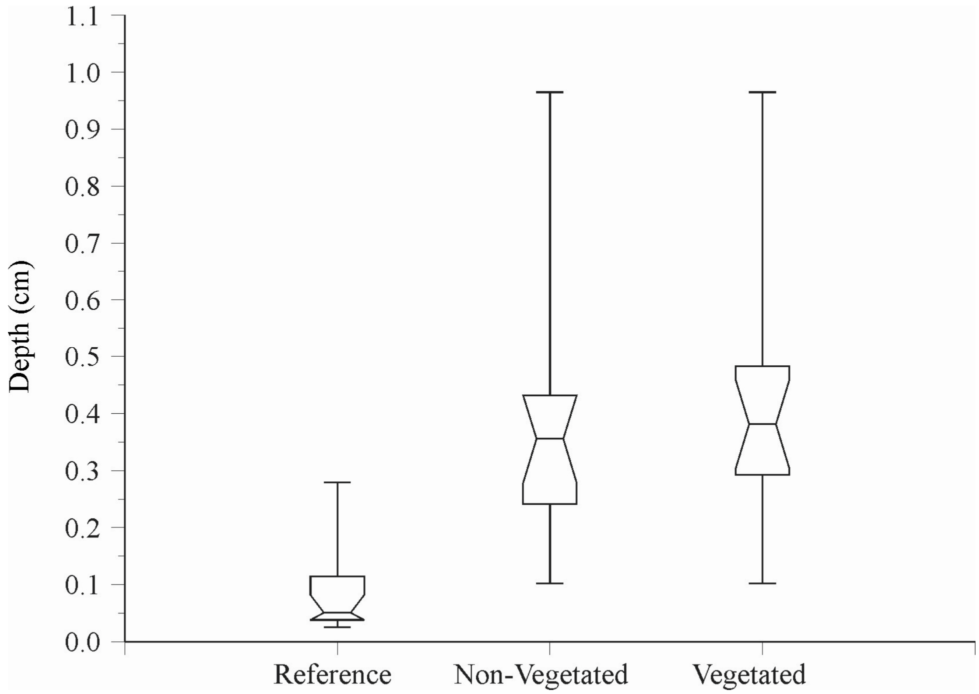

Figure 4.9: Initial abstraction provided by the three treatments. Defined as the accumulated rainfall depth at the time runoff is generated.

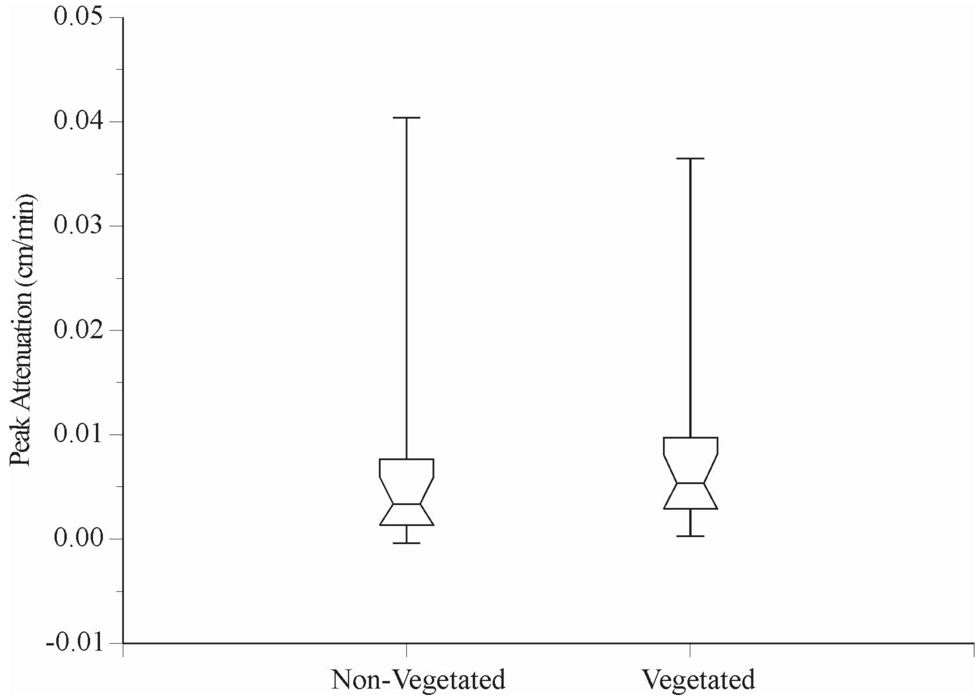

Figure 4.10: Peak discharge attenuation provided by the non-vegetated and vegetated treatment relative to the reference treatment.

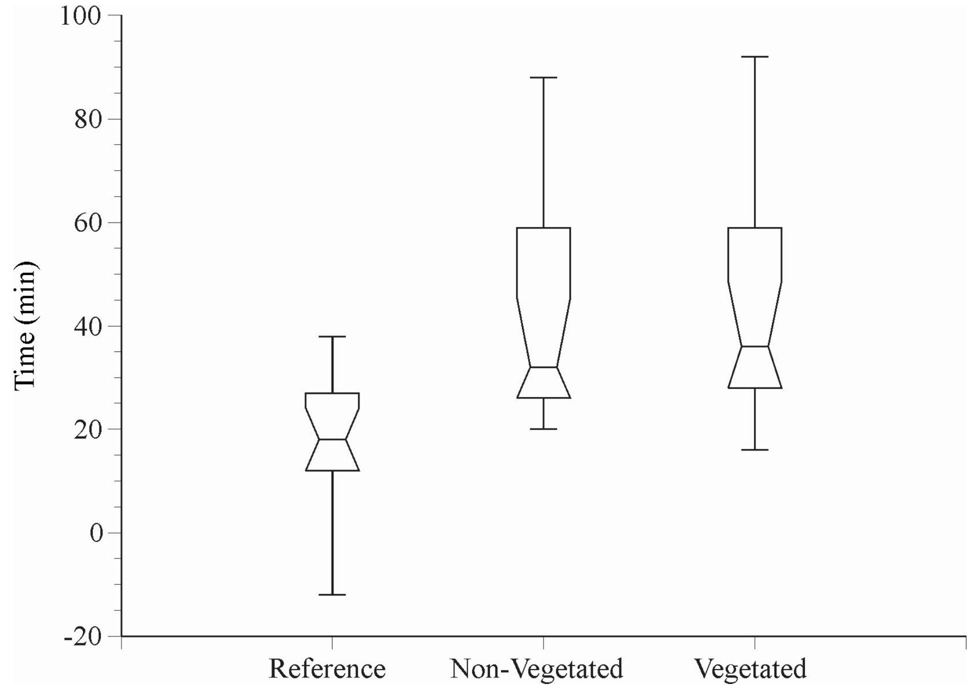

Figure 4.11: Runoff prolongation provided by the three treatments relative to the senescence of precipitation.

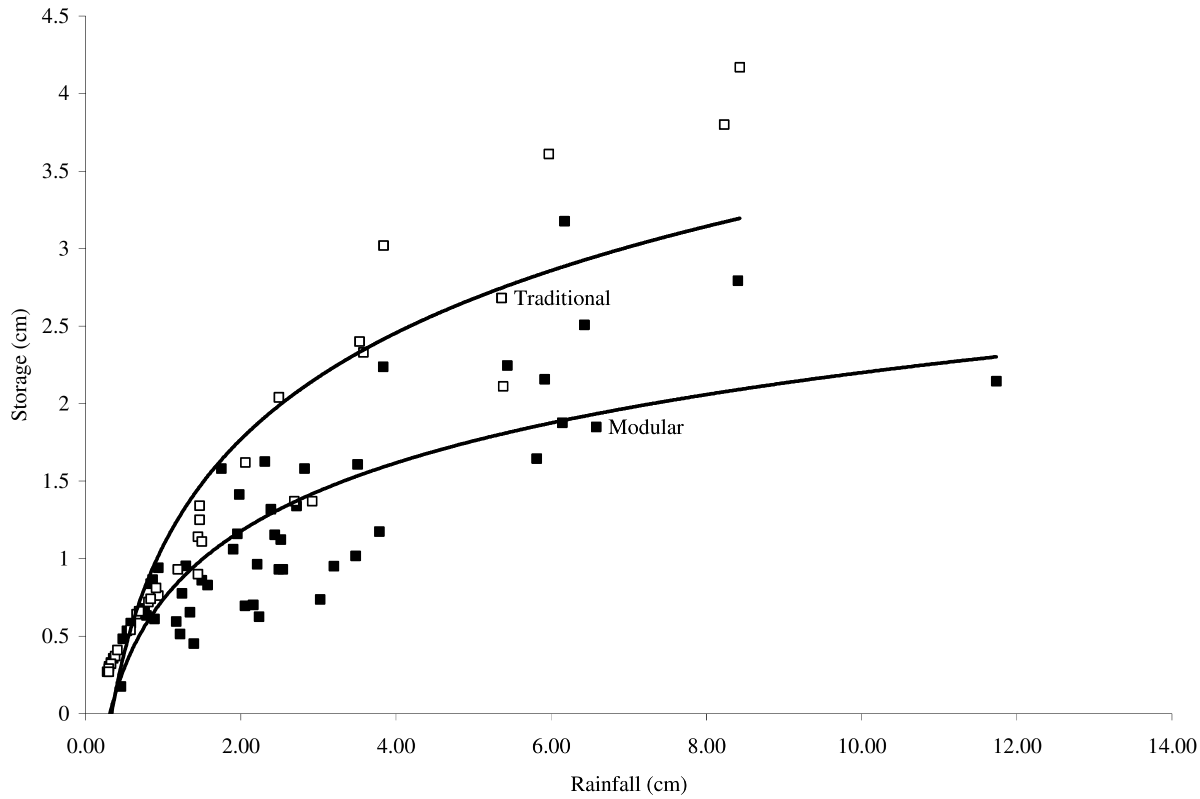

Figure 4.12: Comparison of storage depth as a function of precipitation depth. Compares water retention of traditional green roofs (open squares) and modular green roof (solid squares).

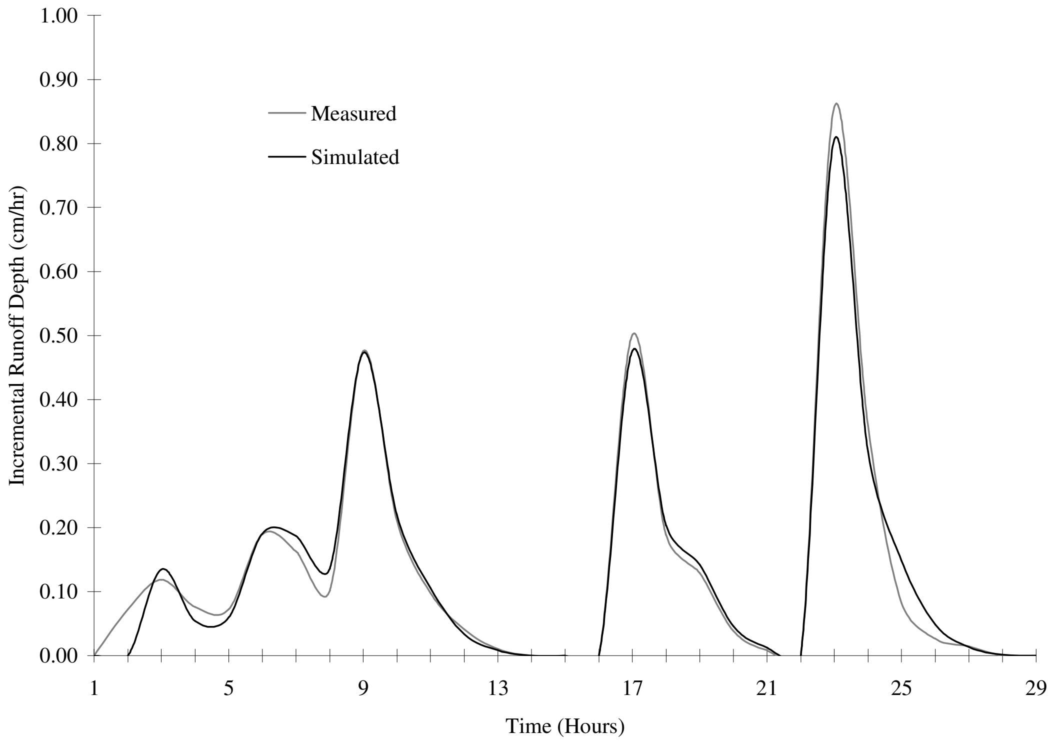

Figure 4.13: Representative storm presenting simulated and observed values modeled using Stella 8.1.

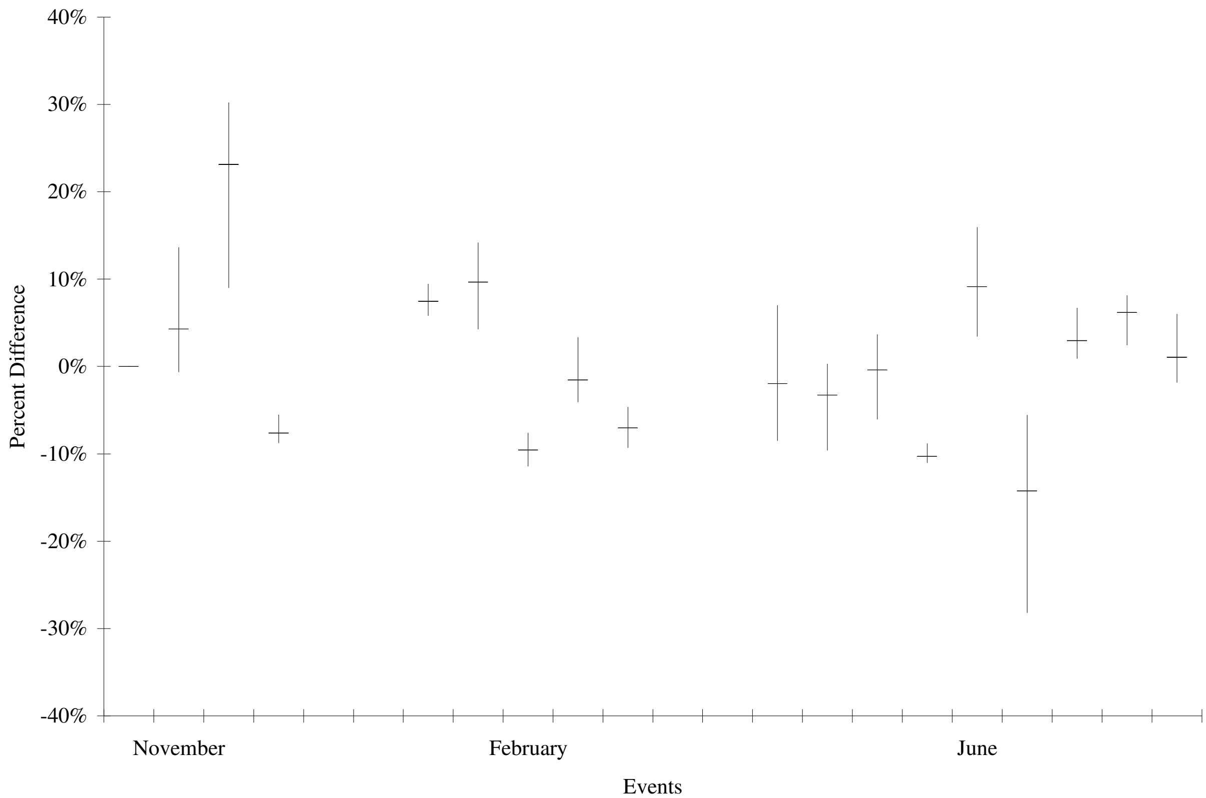

Figure 4.14: Percent difference between simulated and observed values that were modeled using Stella 8.1.

CHAPTER 5

DISCUSSION

Research Conducted

Modern green roof technology is becoming popular in many areas of the United States. Current research, on the ability of green roofs to be used as stormwater management systems at the rooftop scale, has only considered traditional extensive green roofs (BURs). Modular green roof blocks are a new versatile technique to green roofing that simply use engineered soil media and vegetation to capture stormwater from rooftops; no complex water retention liners or other various controlling layers are used. The ability of this technology to be used for stormwater management is unknown. This study quantified stormwater retention and detention of modular green roof blocks using a replicated study consisting of three treatments.

Methods

An automated monitoring system was used to measure runoff from the three treatments. This consisted of pressure transducers mounted inside of stormwater collection containers that measured water depth every minute. Calibration of the transducers was not an easy task, but once adjusted, they were relatively consistent, except for the two that were excluded. The automated monitoring system proved successful in monitoring overall retention, runoff initiation, and runoff termination. However, peak flow determination was difficult due to fluctuating water levels during storm events caused by the runoff falling into the collection containers. This was expected and controlled for using PVC piping, in which the pressure transducer was mounted, but was unsuccessful in eliminating all of the fluctuations. Alternatively, tipping bucket rain gauges could have been used for each of the twelve plots. This design would have eliminated the need for collection containers, which had to be emptied after storm events. This would have been the approach taken if twelve gauges had been available.

One source of error that could not be assessed was the influence of elevation on the experimental units. As described in the methods section, the stormwater collection containers were situated on top of wooden stands approximately 30 cm above the existing rooftop. The combination of the stands and the containers placed the modular blocks approximately 90 cm above the existing rooftop. The influence of elevation, specifically on wind, could have drastically increased the evaporation rates. However, the towers to the east and west, and the two story building to the north, also probably impacted wind flow through the study area. Assessing these issues would have required wind speed measurements at the height of the study area, which was unavailable during the study period.

Due to the study site location, it was expected that rainfall distributions may not be uniform across the site. A randomized complete block design was used to control for this extraneous variation. Statistical analysis proved that expectations were correct, revealing a block effect for the majority of the events. This design is recommended for studies that have replication and are trying to control for irregular rainfall distributions.

Data was analyzed using a repeated measures analysis of variance (ANOVA). This method allows for comparisons across time where different conditions are applied to the treatments. Analysis of covariance was also considered (ANCOVA) for the statistical analysis.

This method features a combination of regression analysis with an analysis of variance. The repeated measures analysis was used because of less data input, and less complex output.

It should be noted, although no water chemistry data was collected, accumulation of algae was noticeable inside all of the vegetated and non-vegetated treatments, and absent from all of the reference treatments. It has been proposed that green roofs could increase the amount of nutrients, specifically nitrates, in rooftop runoff. Our observations provide further evidence to this claim. Future research should attempt to quantify water quality issues, especially nutrients, associated with green roof applications.

Retention and Detention

As expected, the modular green roof blocks were successful in retaining and detaining stormwater runoff. The vegetated treatment retained over 60 cm (43%) of the total rainfall (140 cm) that occurred from October 1, 2004 to September 30, 2005. Average retention for a storm event approximated 67%. These percentages are about 15% less than the findings of VanWoert et al. (2005), and Carter and Rasmussen (2005). The reduced retention capabilities observed in this study might be a product of the absence of a water retention liner or fabric. Both the above mentioned studies were conducted using traditional extensive green roofs that utilized water retention layers, which probably contributed to the larger retention values. Another possibility for the reduced retention observed is the large amount of rainfall that occurred during the study period. 140 cm of rain fell during the twelve month study compared to 55.6 cm over fourteen months for the VanWoert et al. (2005) study and 108 cm over thirteen months for the Carter and Rasmussen (2005) study. It should also be noted that of the 140 cm that occurred, 73% happened during the arbitrary ‘heavy’ events, when low retention percentages were yielded.

When retention was compared among treatments, the vegetated treatment retained the largest amount of stormwater for the observed events. In comparing the vegetated treatment to the reference treatment, all but one event showed statistically significant differences. The vegetated treatment provided a mean percent reduction of almost 59% when compared to the reference treatment. Considering the reference treatment for this experiment provided approximately the same retention of precipitation as the typical gravel ballast rooftops in the VanWoert et al. (2005) and the Carter and Rasmusssen (2005) studies, one could expect this same reduction on a typical rooftop by the vegetated treatment.

In comparing the vegetated treatment to the non-vegetated treatment, very little reduction in stormwater runoff was observed. In fact, for many of the events, the non-vegetated treatments actually retained more stormwater. Although the vegetated treatment retained an average of approximately 1% more of the total rainfall that occurred during the 365 days, within treatment variation makes this difference relatively insignificant.

The non-vegetated and vegetated treatments consistently provided initial abstraction for the 15 events assessed. Initial abstraction, on average, was .5 mm for the reference treatment, 3.6 mm for the non-vegetated treatment, and 3.8 mm for the vegetated treatment. Interestingly enough, the smallest abstractions came during June. Although it was the warmest month, providing increased evaporation, it rained sixteen of the thirty days creating rather wet antecedent soil moisture conditions.

Peak discharge attenuation was also provided by the non-vegetated and vegetated treatments. The vegetated treatment reduced peaks runoff rates, on average, 5.34 E^{-3} cm/min and the non-vegetated treatment 3.36 E^{-3} cm/min when compared to the reference treatment. These reductions were extremely variable due to the problem with the sampling methodology mentioned in the methods. Because the water level in the collection containers fluctuated during storms, the peak runoff rate was, for the most part, arbitrary.

The three treatments all provided runoff prolongation for most events. Median times were 18 minutes for the reference, 32 minutes for the non-vegetated and 36 minutes for the vegetated. Largest runoff prolongation times were observed during the colder months when initial abstraction times were also the largest. This is inconsistent with our expectations because these two detention characteristics should be inversely related. More data analysis is needed to determine if these were isolated occurrences associated with the analyzed events or if this phenomenon is consistent across the data set.

Retention and detention results suggest that evaporative losses from the soil media dominate the reduction of soil moisture between storm events and that the vegetation used in this study, *Sedum sexangular*, does little to contribute to the retention or detention capabilities of modular green roof blocks. These results support those of VanWoert et al (2005). This was to be expected considering Sedums are xerophytes, meaning they are desert species adapted to minimizing water loss. Using this plant type on green roofs may reduce maintenance and the need to irrigate, but it does not provide the best solution for reducing stormwater runoff. Future research should concentrate on how to maximize transpiration rates on green roofs with the use of alternative vegetation.

Modular Green Roof Block versus Extensive Traditional Green Roof

Comparisons of retention between the modular green roof blocks and the adjacent traditional extensive green roof revealed that the modular roof did not retain as much stormwater as the traditional roof. Data collected for the two different study periods showed that the traditional green roof retained approximately 20% more stormwater than did the modular green roof blocks. The study period for the modular roof did experience 30 cm more rainfall than did the study period of the traditional roof leading to more moist antecedent soil conditions. However, for the five events where data collection for the two roofs overlapped, on average, the modular roof again retained about 20% less stormwater, supporting the results comparing different collection periods. Even though the modular roof had approximately 2.5 cm more engineered soil mix, these results suggest that the absence of water retention liners significantly decreased the ability of the modular roof to retain stormwater.

Modeling

Simulation Results

Simulations proved to be relatively accurate for event size runoff totals. Only two of the 18 events analyzed had measured and simulated values that differed more than 10%. Because the model runs on an hourly time step for a one month period, it did not predict timing or peaks as well as overall retention. Much of the variation seen in comparing measured and simulated values could be contributed to the Thornthwaite Evapotranspiration Equation because it calculates average ET over a month by using mean monthly temperature. During a month, average daily temperature can range 15 degrees Celsius. This variation is not accounted for in the model and significantly affects the storage term, due to incorrect evapotranspiration rates. This leads to inflated simulated runoff totals for some storm events and diminished simulated runoff totals for others, but overall monthly runoff totals are consistent with measured values.

This model was a vast simplification of the complex relationships generating the hydraulic response of modular green roof blocks. This model followed that of a reservoir modeling approach; when the storage (field capacity) was exceeded, runoff began and closely mimicked the precipitation. When comparing measured and simulated values, runoff for the measured values consistently began earlier than simulated runoff. This was because, in reality, runoff begins before field capacity is reached. This model was developed more as an intellectual exercise to better understand the hydraulic response of modular green roof blocks and should never be applied in any other manner. Timing and peak flow simulations using this simplified method cannot be construed as an accurate representation, but this model can be used as a stepping stone for creating a model that can accurately predict runoff quantity, timing and peak flow based on a given set of meteorological data.

Understanding the Hydraulic Response

Understanding the processes that control runoff response of green roofs is necessary if an accurate model is to be developed that can predict runoff for a specific designed storm event. Modular green roof blocks differ from traditional extensive green roofs because they do not contain a water retention layer. For traditional extensive green roofs, water percolates through the soil profile to the water retention layer. Before runoff can occur, the water retention layer must become filled, at which point the water can move across this layer to a roof drain. Preliminary analysis, which is consistent with other studies, suggests that this water retention layer is significant in retaining stormwater relative to the water holding capacity of the soil (VanWoert 2005).

Previous research has shown that the hydrograph of traditional extensive green roofs displays retention of stormwater at the beginning of a storm (initial abstraction) until some water volume threshold is reached, after which the hydrograph closely mimics the precipitation pattern (Carter and Rasmussen 2005). This threshold is dependent upon antecedent moisture conditions within the roof (soil and water retention layer) and the overall water storage available within the particular green roof. Because modular green roof blocks lack this extra layer of retention, the hydraulic response of these roofs may not be consistent with traditional extensive green roofs.

We observed cracks in the media of modular green roof blocks after extended dry periods. This raises the issue of macropore flow. Modular green roof blocks consist of an intact soil profile covered with vegetation held within an aluminum block that has predetermined exit points for stormwater (drain holes) at the bottom of each side. For runoff to occur, water must simply reach the exit points and be under enough pressure to move through the drain holes. Macropores develop preferential flow paths for stormwater to move through, creating quick flow or rapid hydraulic response (Uchida et al. 2005). Because modular green roof blocks are intact soil columns, not consisting of water retention layers, it is likely that preferential flow paths developed throughout the course of the study. These paths could drastically alter the runoff response reducing the threshold of water volume needed for runoff to occur. Preferential flow paths would not be thought to influence traditional extensive green roofs in the same fashion. Even though they may exist within the soil profile, they would all lead to the water retention layer, which must become filled or saturated before runoff can occur. Although cracks were observed in the soil that could suggest macropore flow, no data support these allegations. This possibility should be explored further, especially if attempting to construct a more detailed model describing the hydraulic response of modular green roof blocks.

Guidance

Green roofs, whether modular or traditional, are successful at retaining and detaining stormwater at the rooftop scale. Although they provide peak and volume reductions during storms, implementation should only be used when infiltration best management practices (BMPs) are not practical. The ultimate goal of stormwater management should be to maintain the natural hydrology of the site (EPA 2003). This involves infiltrating stormwater back into the ground where it can recharge aquifers, maintain water tables, and sustain base flows. Green roofs store stormwater that is evaporated back into the atmosphere between storms. This practice is similar to evaporation ponds and should be considered an abstraction BMP (Carter and Rasmussen, 2005). In residential or suburban areas, it is not necessary to use stormwater abstraction BMPs and probably not cost effective.

In ultra-urban landscapes, it is often not feasible to maintain the natural hydrology of the site. Under these circumstances, stormwater management goals must change from no-impact development to low-impact development (LID). These situations provide perfect scenarios where green roof implementation can provide an asthetic stormwater management facility and substantial benefits to our streams and rivers.

It is important that stormwater engineers, management agencies, and elected officials consider that data collected in northeast Georgia will not necessarily be applicable to all locations. Stormwater retention and detention provided by green roofs are as much a product of climatic conditions as they are green roof specifications. This is why it is necessary to develop accurate models that can predict retention and detention of green roofs based on meteorological data and physical characteristics of the green roof.

CHAPTER 6

THESIS CONCLUSION

Managing stormwater in densely urbanized areas has proven to be a challenge over the past few decades. Providing sufficient treatment of stormwater quantity and quality, which minimizes impacts on physical and biological attributes of receiving waterways, poses difficult problems. Designating large areas of valuable land to treat and dispose of stormwater is just not an option for decision makers, and treating the quantity of stormwater generated by these areas can not be achieved on small parcels. In these ultra-urban areas, rooftops comprise a large percentage of total impervious surfaces and provide unique opportunities for stormwater management. Modern vegetated rooftops, or green roofs, have been used for decades in Europe to mitigate stormwater runoff, energy costs, and heat islands. New green roof technology is constantly being developed and product testing is necessary to evaluate their capabilities. In this study, we monitored stormwater runoff from modular green roof blocks to determine if they are as effective at stormwater management as traditional green roof designs.

Stormwater retention and detention was quantified for modular green roof blocks in northeast Georgia. Results showed that modular green roof blocks successfully retained and detained stormwater during the one year study. For the majority of the small frequent events, no runoff was observed from the non-vegetated and vegetated treatments. Results for this study were compared to a traditional extensive green roof located adjacently. Although more comparable data is needed to accurately assess the differences in retention, the traditional extensive green roof (BUR) appears to be about 20% more effective at retaining stormwater runoff.

Even though the modular green roof blocks did not retain as much stormwater as the traditional extensive green roof, they still serve as effective tools for retaining and detaining runoff. Versatility is often one of the most important considerations when investing in technology such as green roofs. Modular green roof blocks provide this versatility and do not require any installation expertise.

Distributed BMP stormwater management systems are becoming increasingly common. Disconnecting impervious surfaces from the stormwater conveyance network has proven successful in protecting water quality, quantity, and habitat. Green roofs, including modular green roof blocks, provide an alternative BMP to consider when developing stormwater plans that limit impervious cover and maintain the natural hydrology of a site.

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