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EXTENSIVE GREEN ROOFS IN MISSISSIPPI: AN EVALUATION OF STORMWATER RETENTION UNDER LOCAL CLIMATIC CONDITIONS

By

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EXTENSIVE GREEN ROOFS IN MISSISSIPPI: AN EVALUATION OF STORMWATER RETENTION UNDER LOCAL CLIMATIC CONDITIONS

By

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Green roofs are increasingly being used in the United States to mitigate the negative effects of impervious surfaces on aquatic ecosystems. Though performance of these systems varies with climate, little research has been conducted in the Southeastern U.S., and no prior research has been conducted in Mississippi. An experiment was conducted to determine the effect of soil depth and roof slope on the stormwater retention of green roofs in Mississippi's hot, humid climate. Simulated roof platforms were constructed to investigate two soil depths and two slopes, each replicated three times and planted with four species of *Sedum*. The green roof platforms significantly reduced runoff depth when compared with total rainfall depth. Soil depth and slope both significantly affected retention, with higher retention seen with increasing soil depth and lower retention seen with increasing slope. These results indicate that green roofs can be an effective tool to reduce runoff in Mississippi.

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TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Background

The relationship between increased urbanization and increased impervious area has long been recognized (Arnold Jr and Gibbons 1996). Furthermore, research has shown that the impervious area resulting from urbanization disrupts the hydrologic cycle and leads to severe degradation of local and downstream aquatic ecosystems (Booth 1997). Conventional development practices typically address the high levels of runoff from impervious surfaces through highly-engineered methods of conveying runoff away from the developed land, further exacerbating the problems associated with a disrupted hydrologic cycle(Prince George's County 1999). In contrast, Low Impact Development (LID), originated by Maryland’s Prince George’s County, seeks to diminish the effects of increased urbanization and impervious surface area. The LID method encourages thoughtful site design in which the highest priority is on preserving as much of a site in its undisturbed, predevelopment condition as possible. In the event that disturbance is unavoidable, the goal should be to minimize damage to the soils, vegetation, and aquatic systems on and off the site with Best Management Practices (BMP) such as bioretention facilities, vegetated swales, water collection systems, permeable pavements, and vegetated green roofs (Dietz 2007).

According to the U.S. Census Bureau, though the overall population of Mississippi over the period from 2000 to 2008 grew a mere 3.3%, there was a large shift towards urban areas (U.S. Census Bureau). Given the strong association between urbanization and increased impervious area, and between impervious area and the degradation of aquatic ecosystems (Booth and Jackson 1997), any method that might be used to lessen the rate of runoff from these impervious areas has the potential to mitigate the negative impacts of urbanization. With awareness about the negative effects that development has on our water resources spreading, the use of LID tools to mitigate these negative effects will likely become more common. As private developers and government agencies begin considering widespread implementation of these tools, local data on the effectiveness of these tools will be increasingly requested, if not required (Taylor 2006; Sale and Berkshire 2004). Since green roofs have proven successful in other climates in helping to mitigate the negative effects associated with urbanizing areas, their performance and possible implementation in the Mississippi climate should be investigated.

1.2 Purpose of the Study

This thesis seeks to expand the current body of knowledge regarding green roofs and stormwater runoff mitigation. While similar research has been conducted in Europe and other regions of North America, few studies have been conducted in the Southeastern United States, and no green roof research has been conducted in Mississippi. There is currently no data that designers, developers, or policy-makers can use when considering the implementation of green roofs in Mississippi.

More specifically, this study attempts to determine the stormwater retention of green roofs under Mississippi's climatic conditions and how two separate design variables might affect this retention. The following research questions were developed in order to investigate green roof retention in Mississippi:

- What effect do green roofs have on water retention when compared to conventional roofs?
- What effect does green roof soil depth have on stormwater retention?
- What effect does green roof slope have on stormwater retention?

1.3 Organization of Thesis

The succeeding portion of this paper is organized into a Literature Review, a Methodology chapter, a Results chapter, and a Discussion and Conclusions chapter. The Literature Review provides background information on green roofs and surveys the published research related to green roofs and stormwater runoff. The Methodology chapter describes the experiment that served as the data collection vehicle and the statistical procedures used to subsequently analyze the data. The Results chapter summarizes the results of the experiment and statistical analyses. The Discussion and Conclusions chapter describes the limitations of the study, discusses the results in the context of related research, and provides some suggestions for further research.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This literature review provides an overview of research on green roofs and their associated environmental benefits. First, a brief history of the green roof and its evolution into the contemporary green roof is discussed. Second, a further description of the contemporary green roof and its component parts is provided. Third, a review of research on several of the primary environmental benefits associated with green roofs is conducted. Last, an overview of methods which prior researchers have used to study green roof function is given.

2.2 Brief History of Green Roofs

Evidence suggests that humans have been placing vegetation atop man-made and inhabited structures since at least 4000 B.C. These early vegetated roof areas were likely used as functional extensions of the interior spaces created by the structures' walls, and were very similar to elaborate ground-level gardens in that their relatively deep levels of soil allowed a wide variety of vegetation types, including trees. Beginning in the 17th Century, Norwegians began placing thin layers of soil planted with grasses on their roofs in order to provide insulation during long, frigid winters. This tactic was also used during the 19th century by settlers of the Great Plains in North America (Osmundson 1999).

The genesis of the contemporary green roof can be traced to German efforts in the early 20th century to reduce solar degradation of roofing materials and the fire risk associated with tar roofing by placing thin layers of sand and gravel above the tar. In time, plants sprouted from the sand/gravel mix, and in some instances this vegetation was allowed to stay and to develop into meadow-like landscapes (Köhler 2003; Getter and Rowe 2006). A growing environmental awareness among the scientific community and the general populace of Germany during the 1960's and 1970's, coupled with political incentives to innovate on this front, led to many experimental building projects that sought to integrate the built and natural environments. Several books that were published and widely circulated in Germany promoted the concept of roof greening as something for the common man and the common structure. The concept spread like the fire that these roofs were initially developed to suppress, into scientific research, product development, and the setting of design and construction standards (Dunnett and Kingsbury 2004; Oberndorfer et al. 2007).

2.3 Contemporary Green Roof Design

The *Forschungsgesellschaft Landschaftsenwicklung Landschaftsbau* (FLL), or the German Landscape Research, Development and Construction Society, developed the first *Guidelines for the Planning, Execution and Upkeep of Green-Roof Sites*, which has guided the design and implementation of green roofs worldwide. In this document, first published in 1982 and updated as recently as 2008,two general classes of green roofs, based on soil depth, were defined: intensive and extensive (Dunnett and Kingsbury 2004). An intensive green roof is most similar to the traditional concept of a garden roof, which may focus primarily on the active use of the roof space and contain relatively deep soil depths (>6 in.) that allow the cultivation of shrubs and trees. Extensive green roofs have very shallow soil depths (≤ 6 in.) and primarily focus on the associated environmental benefits such as stormwater retention or reduction in energy use rather than the active use of space (Weiler and Scholz-Barth 2009).

At the core of all green roof systems are three essential components: waterproofing, soil, and plants. In order to ensure that the core components are able to perform their respective duties of keeping the structure watertight and the plants in a healthy state, several other components are usually included. Among those are a specialized drainage layer, a separation layer to keep the drainage layer free of soil particles, and a root barrier to inhibit the plants from compromising the waterproof membrane (Dunnett and Kingsbury 2004; Weiler and Scholz-Barth 2009). Figure 2.1 depicts the typical components included on extensive green roofs

The waterproof membranes used beneath the vegetated portion of green roofs do not differ from membranes used on typical commercial low-slope roof assemblies. Common waterproof membranes include hot or cold-applied rubberized asphalt, built-up bitumen, modified bitumen, polyvinyl chloride (PVC), thermoplastic olefin (TPO), and ethylene propelynedienemonomer (EPDM) (Green Roofs for Healthy Cities 2007).

Root barriers, whether blocking roots via physical or chemical means, are usually installed atop the membrane to inhibit plant roots from jeopardizing the waterproof membrane. Though some view the inclusion of a root barrier as unnecessary for roofs planted with low-growing groundcovers such as *Sedum*, most roof assemblies include them as a precautionary measure against potential volunteer plants with aggressive root systems. Common root barriers include impervious concrete, high-density polyethylene

(HDPE), impregnated copper, copper lining, and herbicide embedded fabric. TPO and PVC waterproof membranes offer root resistance on their own and do not require the addition of a root barrier (Green Roofs for Healthy Cities 2007).

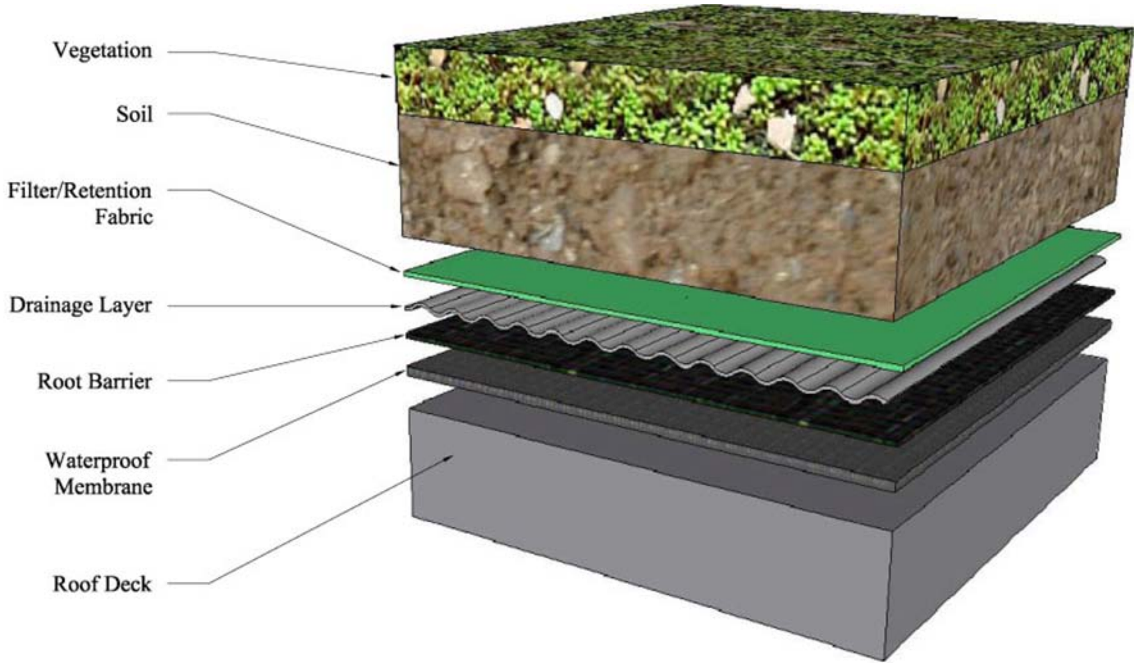


Figure 2.1 Illustration of typical extensive green roof components.

Water that exceeds the absorption and retention capacity of the green roof escapes from the roof via a specialized drainage layer positioned directly above the waterproof membrane and/or root barrier that directs water to roof drains. The drainage layer ensures the durability of the waterproof membrane, the building structure's integrity, and the survival of green roof vegetation. Drainage layers can be constructed of a variety of materials, but are typically lightweight plastic or polystyrene based forms, foam materials, granular mineral mixtures (gravel), rockwools, or a combination of one or more of these materials. The effectiveness of the drainage layer depends on the placement of a filter layer above the drainage layer in order to prevent the downward migration of soil particles that could impede drainage. In many cases, a retention mat, typically composed of felt or other absorbent fibers, is included in conjunction with the filter layer in order to retain water and then slowly release it to the root zone (Weiler and Scholz-Barth 2009).

Green roof soil, or growing media, is a lightweight, engineered mix of inorganic and organic components designed to support plant growth. The inorganic or mineral-based portion of the soil mix may contain sand, silt, gravel, and/or expanded aggregate. The organic portion of the mix is composed of composted organic matter that has reached a stable (non-decaying) state. The specific materials used as growing media components as well as the exact proportion of inorganic to organic components are governed both by local availability and project goals (Green Roofs for Healthy Cities 2008).

The plants specified will vary based on project goals, local environmental conditions, desired plant characteristics, and the depth and composition of the soil. The most common types of plants chosen for green roofs are low-growing, spreading groundcovers with a high tolerance to drought conditions and the low nutrient levels typical of green roof soils. The majority of these plants come from the *Crassulaceae* family, with the most frequent genus used on green roofs being *Sedum*, a group containing nearly 600 species (Snodgrass and Snodgrass 2006). *Sedum*'s ability to survive extreme drought conditions is due to its ability to store water in its leaf tissue for extended periods and to alter its metabolism, and thus transpiration rate, through the process of Crassulacean acid metabolism (CAM) (Snodgrass and Snodgrass 2006; Voyde et al. 2010). While plants in other genera and with other growth habits are also used, they frequently require supplemental irrigation to survive the extreme growing conditions present on a roof (Snodgrass and Snodgrass 2006).

2.4 Green Roof Benefits

Many environmental and/or economic benefits have been associated with the implementation of green roofs. Among the primary environmental benefits of green roofs are the reduction of energy use and the urban heat island effect, increased life span of waterproof membranes, and mitigation of stormwater runoff (Getter and Rowe 2006). Other benefits include, but are not limited to increased aesthetic value, reduction in air and noise pollution, increased biodiversity and carbon sequestration, wind buffering, and fire protection (Osmundson 1999).

2.4.1 Energy Use and the Urban Heat Island Effect

Green roofs can greatly diminish an individual building's energy needs through direct shading, evapotranspiration, and the combined insulative properties of vegetation and soil (Köhler et al. 2002; Peck et al. 1999; Liu and Bass 2005). In a study in Greece, Niachou et al. (2001) discovered that green roofs reduced energy needed for cooling by as little as 2% and as much as 48%, depending on the amount of non-green roof insulation in the structure. The majority of energy savings attributable to a green roof result from a reduction in cooling loads during warm weather; though some reduction in heating loads has been found during cold weather, that reduction has been less than half that of the reduction in cooling loads during warm weather (Saiz-Alcazar and Bass 2005; Santamouris et al. 2007; Sfakianaki et al. 2009).

Wong et al. (2003) recorded air temperatures directly above a green roof that were as much as 86° F lower than a comparable, conventionally-surfaced roof. This has implications that extend much further than that of an individual building's energy consumption and into the possibility of mitigating the urban heat island effect, a circumstance whereby the overall temperature of an urban area is elevated above that of surrounding rural areas due to the proliferation of impervious surfaces that reduce cooling through evapotranspiration; low-albedo surfaces such as rooftops, streets, and parking lots that absorb, rather than reflect heat; and the blocking of surface heat from being released into the atmosphere during nighttime hours by dense aggregations of tall buildings (Rosenzweig et al. 2009; Susca, Gaffin, and Dell'Osso 2011).

2.4.2 Increased Lifespan of Waterproof Membrane

In addition to the effects that they can have on energy, the direct shading and insulative qualities of the plants and soil also serve to protect the waterproof membrane from degradation. This is achieved by reducing the exposure to the ultraviolet radiation that tends to make traditional waterproof membranes brittle, and by reducing the fluctuating daily surface temperatures that cause expansion and contraction of the membrane (Getter and Rowe 2006). Some have estimated that a green roof can more than double the expected life of the waterproof membrane (Peck et al. 1999; Oberndorfer et al. 2007). However, because the modern green roof movement in North America is just beginning to emerge and most roofs are less than fifteen years old (typical lifespan of conventional waterproof membrane), the lifespan of waterproof membranes on green roofs on this continent can only be estimated based on historic performance in Europe. Many German green roofs are more than thirty years old, and one green roof in Berlin has survived without any major repairs for ninety years (Porsche and Köhler 2003).

2.4.3 Mitigation of Stormwater Runoff

Though green roofs may have the ability to mitigate many of the negative effects of urbanization such as increased urban temperatures, decreased air quality levels, and decreased biodiversity, many consider the mitigating effects that green roofs can have on stormwater runoff quantity and quality to be their primary benefit (Van Woert et al. 2005; Getter and Rowe 2006; Monterusso et al. 2004; Oberndorfer et al. 2007).

2.4.3.1 Stormwater Runoff Quantity

Numerous studies have indicated that the implementation of extensive green roofs can be a suitable tool to reduce urban runoff, and that depending on the type of green roof system used, can reduce annual runoff by 45-100% and can significantly delay the initiation of runoff when compared to a conventional roof (Mentens, Raes, and Hermy 2006; Monterusso et al. 2004; Van Woert et al. 2005; Moran 2005; Villarreal and Bengtsson 2005; Getter, Rowe, and Andresen 2007; Simmons et al. 2008; Schroll et al. 2011; Berghage et al. 2007). This reduction in runoff occurs via the green roof soil, vegetation, and retention mats, if present, intercepting and retaining water. The specific amount of water retained by a green roof depends on design factors such as soil depth and composition, plant species composition, and roof slope as well as local climatic factors such as rainfall intensity, rainfall duration, and temperature (Getter, Rowe, and Andresen 2007; Simmons et al. 2008). Each of these factors and their contribution to retention will be discussed in following sections.

2.4.3.1.1 Soil Depth and Composition

The depth of green roof soil can affect the amount of water retained. Van Woert et al. (2005) found when measuring cumulative rainfall over a 14-month study period that a 1.57 in. soil depth on a roof with a 2% slope retained 2% more runoff during light (<0.08 in.) events, 2.6% more during medium (0.08-0.24 in.) events, and 0.9% more during heavy (>0.25 in.) events when compared to a 0.79 in. soil depth on a roof with a 2% slope. Across all rain categories, roofs with 1.57 in. soil depth and 2% slope retained

70.7% and roofs with 0.79 in. soil depth and 2% slope retained 69.9%. Similarly, roofs with 2.4 in. soil and 6.5% slope retained 0.9% more in light events, 1.5% more in medium events, and 2.5% more in heavy events when compared to roofs with a 6.5% slope and 1.57 in. soil. Overall, roofs with 2.4 in. soil and 6.5% slope retained 68.1% of cumulative rainfall, while roofs with 1.57 in. soil and 6.5% slope retained 65.9 %. These differences, though slight, were found to be statistically significant in all except for heavy events (Van Woert et al. 2005).

In conducting a review of 18 German studies, Mentens et al. (2005) discovered that green roofs with a median soil depth of 5.91 in. retained 75% of annual rainfall and that extensive green roofs with a median substrate depth of 3.94 in. retained only 45% of annual rainfall.

2.4.3.1.2 Plant Species Composition

Plants affect stormwater retention by interception of rainfall by the vegetative canopy, by the absorption and storage of moisture in plant tissues, and subsequently through transpiration of moisture back into the atmosphere. Because plant species differ in their canopy structure, water-holding capacity, and the amount of vegetative litter they contribute to the soil, the hydrologic performance of a green roof depends on plant species composition (Dunnett et al. 2008; MacIvor and Lundholm 2011; Nagase and Dunnett 2012). For instance, in a study investigating the stormwater runoff from green roofs planted with the three functional plant groups common on green roofs (succulents, forbs, and grasses), Nagasse and Dunnett (2012) found that succulents, *Sedum* in particular, had the highest runoff (lowest retention) and grasses had the lowest runoff (highest retention), with forbs falling in between. Lundholm et al.(2010) saw higher retention rates on green roofs planted with multiple functional plant groups when compared to roofs planted with only one functional plant group.

2.4.3.1.3 Roof Slope

Roof slope may also affect the stormwater retention of green roofs. Two studies at Michigan State University found that retention decreased with increasing slope, though across all slopes, cumulative mean retention over the duration of the studies ranged from 65.9% to 85.2% (Van Woert 2005; Getter 2007). Van Woert et al. (2005) saw cumulative retention decrease from 70.7% to 65.9% when slope was increased from 2% to 6.5% on green roof platforms with 1.57 in. soil. When retention percentages were considered on an event-by-event basis, retention was considerably higher, ranging from a high of 87% on platforms with a 1.57 in. soil depth and a 2% slope to a low of 83.8% on platforms with a 1.57 in. soil depth and a 6.5% slope. In investigating 2%, 7%, 15%, and 25% sloped roofs with 1.57 in. soil, Getter, Rowe, and Andresen (2007) also saw retention decrease consistently with increasing slope, with 2% sloped roofs retaining 85.2%, 7% sloped roofs retaining 82.2%, 15% roofs retaining 78.0%, and 25% sloped roofs retaining 75.3% over the entire study period. However, the results from these two studies contradicted the findings of several German studies in which slope appeared to have absolutely no effect on retention (Mentens, Raes, and Hermy 2006). In a study of individual rain events, Villarreal and Bengtsson (2005) determined that retention decreased with increasing slope, but that the difference was only significant under initial dry conditions. This suggests that weather patterns may be an important factor in determining to what degree slope affects stormwater retention.

2.4.3.1.4 Climate

Green roof studies have consistently shown that rainfall depth and retention percentage are inversely related; the larger the individual rain event, the lower the retention (Van Woert et al. 2005; Getter, Rowe, and Andresen 2007; Carter and Rasmussen 2006; Villarreal and Bengtsson 2005; Van Seters, Rocha, and MacMillan 2007; Teemusk and Mander 2007). Retention is also strongly related to the period of time between rainfall events, commonly referred to the antecedent dry weather period (ADWP) (Stovin, Dunnett, and Hallam 2007; Stovin 2009). The effect that the ADWP will have on recharge, and therefore on retention in subsequent events, is determined by the length of the ADWP, the temperature during the period, and the type of vegetation present (Berghage et al. 2007; Hathaway, Jennings, and Hunt 2008; Voyde et al. 2010; Schroll et al. 2011).

Many others have noted that climatic factors affect the stormwater performance of green roofs (Oberndorfer et al. 2007). In fact, virtually every study mentions as a limitation in their study, that the results would likely differ in other climates. Though the average annual retention amount for green roofs studied in a variety of climates has been approximately 63%, the amount retained by an extensive green roof in a particular climate will vary with rainfall intensity and duration, temperature, humidity, and other climatic factors (Stovin, Dunnett, and Hallam 2007; Simmons et al. 2008; Dietz 2007; Moran 2005; Monterusso et al. 2004; Van Woert et al. 2005).

2.4.3.2 Stormwater Runoff Quality

Some have suggested that green roofs will help to improve water quality through the reduction of annual runoff volumes and through pollutant removal by the plants and soil media (Osmundson 1999; Scholz-Barth 2001). Until recently, this assumption had gone unchallenged and un-researched. Recent studies have indicated that the effect that green roofs have on the quality of runoff is most highly dependent on factors such as soil media composition and fertilizer applications (Moran 2005; Retzlaff et al. 2008; Hathaway, Jennings, and Hunt 2008), but may also be affected by soil depth and climate (Teemusk and Mander 2007; Berndtsson, Bengtsson, and Jinno 2009; Berghage et al. 2009).

Retzlaff et al. (2008) saw elevated nitrate concentrations from their test green roofs, but saw no significant difference in runoff concentrations between a 5cm soil depth and a 10 cm soil depth. In some contrast, Berndtsson, Bengtsson, and Jinno (2009) reported higher rates of nitrate and phosphorous export in shallow substrate extensive green roofs than in those with deeper substrate intensive green roofs, and speculated that this difference was largely due to a difference in vegetation rather than soil depth. Likewise, Teemusk and Mander (2007) found elevated concentrations of nitrate and phosphorous in green roof runoff, with higher amounts being flushed from the roof during high intensity rain events than during more moderate or low intensity events. A study in Pennsylvania found higher concentrations of nitrate and phosphorous during the summer months, but noted that due to the reduction in runoff quantity, the total annual amount of nitrate released to the environment was significantly less from the green roofs than from the control roofs (Berghage et al. 2009). From these studies, it is clear that because seasonal variations affect the export amount of nitrate and phosphorous, stormwater quality performance will differ with varying climates.

2.5 Data Collection Methods

Studies that have been conducted in order to quantify the effects of various green roof design factors on stormwater runoff quantity have been performed on both full-scale green roofs and on simulated green roof modules.

Full-scale green roof monitoring programs have been conducted on existing green roofs as well as roofs constructed specifically for the purpose of collecting data (Moran 2005; Carter and Rasmussen 2006; Teemusk and Mander 2007). In order for comparisons to be made between the green and conventional roof, great care must be taken in order to ensure that the roofs contain the same physical parameters, all runoff can be collected, and its source can be determined (Taylor 2006). When performed on existing roofs, these studies often take the form of a paired watershed study in which data from a green roof is compared with data from a control roof with no replication (Carter and Rasmussen 2006). Dunnett, Nagase, and Hallam (2008) achieved control over physical parameters and provided for replication and controls through utilizing a timber framework to create individual test beds on a new full-scale green roof.

Because green roofs can cost up to twice as much as a traditional roof to install (Getter and Rowe 2006) and there are relatively few existing green roofs in most areas, many researchers conduct research on small-scale simulated roof platforms. Researchers at Michigan State University began conducting studies utilizing simulated roof platforms when Ford Motor Company approached them seeking advice on the construction of a 10.4 acre extensive green roof on a new factory building in Dearborn, MI (Rowe; Monterusso et al. 2004). Constructing simulated roof platforms allows researchers precise control over the parameters of the green roofs and the ability to replicate each treatment (Mentens 2003).

Van Woert et al. (2005) conducted a study in which the effects of roof surface, slope, and media depth on stormwater retention were quantified. The 8 x 8 ft. roof treatments, each with three replications, were arranged in a completely randomized design. Each roof platform was configured so that all runoff would drain to a single point where it was measured with a tipping bucket rain gauge and recorded by a central data-logger. Many others have used simulated roof platforms in order to study the performance of green roof systems. Retzlaff et al. (2008) constructed 2 x 2 ft. green roof platforms, collected runoff from each platform in individual containers, and took quantity and quality measurements from the collected runoff.

CHAPTER III

METHODOLOGY

3.1 Site Description

A controlled experiment was conducted on a research plot at Mississippi State University's South Farm, Mississippi State, MS USA (33.424° N, 88.792° W, elevation 325 ft). The climate is considered a humid subtropical climate type, represented by typically mild winters without extended periods of below-freezing temperatures; long, hot, humid summers; and no regularly recurring wet or dry season (National Climatic Data Center 2005). The Mississippi State area receives an average annual rainfall of 55.45 in., with the period of greatest rainfall falling between November and June. March is historically the wettest month, receiving an average of 6.07 in. of rain. October is the driest month, receiving an average of 3.35 in. of rain. The highest annual temperatures are seen in July, with a monthly average high of 91.3° F. The lowest annual temperatures are seen in January, with a monthly average high of 51.9° F (National Climatic Data Center 2004).

3.2 Roof Platforms

Eighteen roof platforms were constructed and placed on the research plot during the spring and summer of 2010 (Fig. 3.1). In order to study two soil depths and two slopes, twelve platforms simulated typical extensive green roofs. The remaining six platforms served as control roofs, three each for the two slopes studied. All platforms were constructed with treated pine lumber and have roof surface areas of 16 ft^2 (4 x 4 ft.).

The twelve green roof platforms include the addition of eight inch side walls to contain the green roof substrate (Figs. 3.2, 3.3).

Figure 3.1 Overall view of roof platforms at the study site.

The green roof platforms (deck and side walls) were covered with a fully-adhered SBS-modified bitumen waterproof membrane (*Sopralene Flam GR*, Soprema*,* Wadsworth, OH), one of the traditional treatments for commercial flat roofs. Of the remaining six platforms, three were waterproofed with a fully-adhered SBS-modified bitumen waterproof membrane and three were waterproofed with asphalt shingles. Two-inch high sheet-metal sides were added to the two sloped sides (not the back) of the lower-sloped control roofs after the fourth rain event, upon discovering water escaping collection by running off the sides of these roofs.

Platforms simulating green roofs contained a drainage layer with an integrated moisture retention mat (*Enka Retain & Drain 3211,*Colbond Inc.,Enka, NC). The drainage layer consists of a composite a non-woven polyester fabric and a synthetic hydrophilic absorbent mat attached to the upper side of a polypropylene drainage core of fused, entangled filaments (Fig. 3.4). The 0.165 inch thick retention mat can retain 0.11 gal/ft^2 of water. The overall thickness of the integrated drainage/retention layer is 0.61 inches. The drainage/retention system allows any water that exceeds the water storage capacity of the retention mat and soil to drain through the entangled polypropylene filaments and exit the roof. The sloped green roof platforms also contained a soil stabilization mat (*EnkaMat 7010,* Colbond Inc., Enka, NC). A gap was left on the low side of each platform to allow runoff to exit the roof (Figs. 3.2, 3.3).

An engineered green roof growing media (*ERTHHydrocks Lightweight Soil Media-Extensive,* ERTH Products, Peachtree City, GA) was placed directly over the drainage/retention layer. This soil mix consists of 80% Hydrocks Rotary Kiln Expanded Clay with particle sizes ranging from 3/8 to 3/16 in., 15% nutrient grade compost manufactured using a mixture of peanut shells and biosolids, and 5% USGS sand (Fig. 3.5).

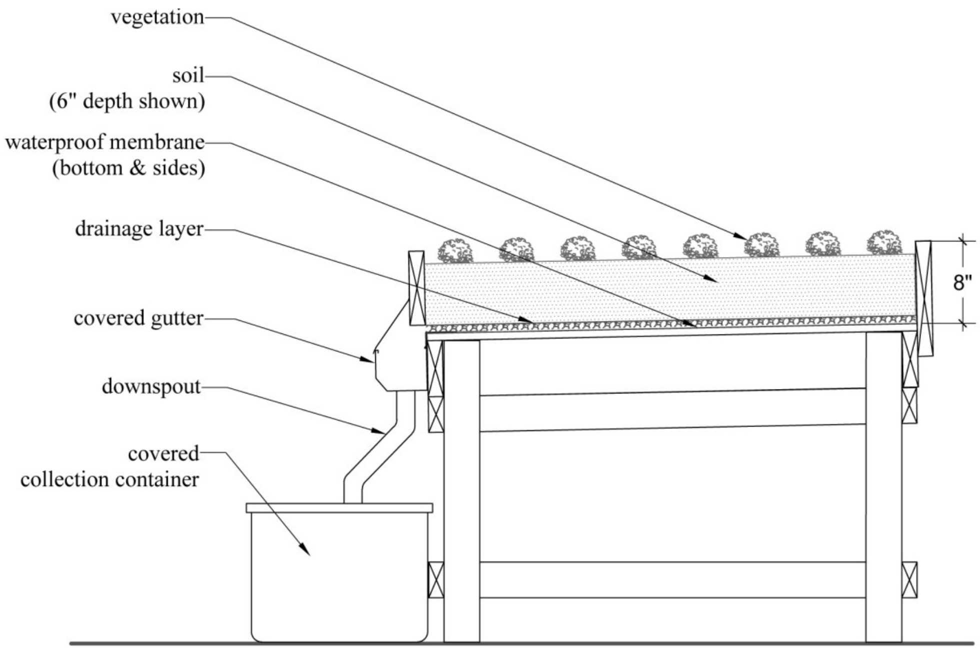


Figure 3.2 Section of roof platform with 2% slope.

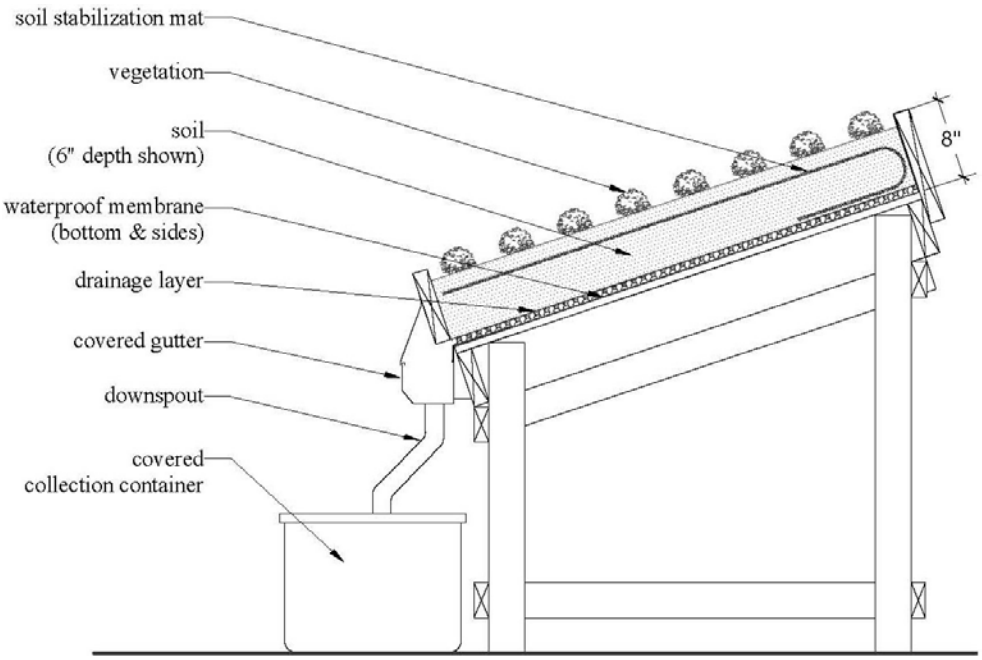


Figure 3.3 Section of roof platform with 33% slope.

Figure 3.4 Two views of integrated drainage/retention layer (*Enka Retain & Drain 3211*). Top image shows filter/retention fabric on upper side of product. Lower image shows entangled polypropylene filaments on underside of product.

Figure 3.5 Engineered green roof soil **(***ERTHHydrocks Lightweight Soil Media-Extensive*). Mix is 80% expanded clay particles, 5% USGS Sand, 15% nutrient-grade compost.

3.3 Treatments

Two different slopes were studied with two different substrate depths for each slope; each replicated three times (Fig. 3.6). Nine platforms were set at a 2% slope, representing the slope of conventional flat roofs, with three control platforms representing conventional un-vegetated roofs, three platforms representing extensive vegetated roofs with a 4 in. substrate layer, and three platforms representing extensive vegetated roofs with a 6 in. substrate layer. The remaining nine platforms were set at a 33.3% slope, representing low to moderately-low pitched roofs, with three control platforms representing conventional un-vegetated sloped roofs, three platforms representing extensive vegetated sloped roofs with a 4 in. substrate layer, and three platforms representing extensive vegetated sloped roofs with a 6 in. substrate layer. All platforms were oriented towards the south.

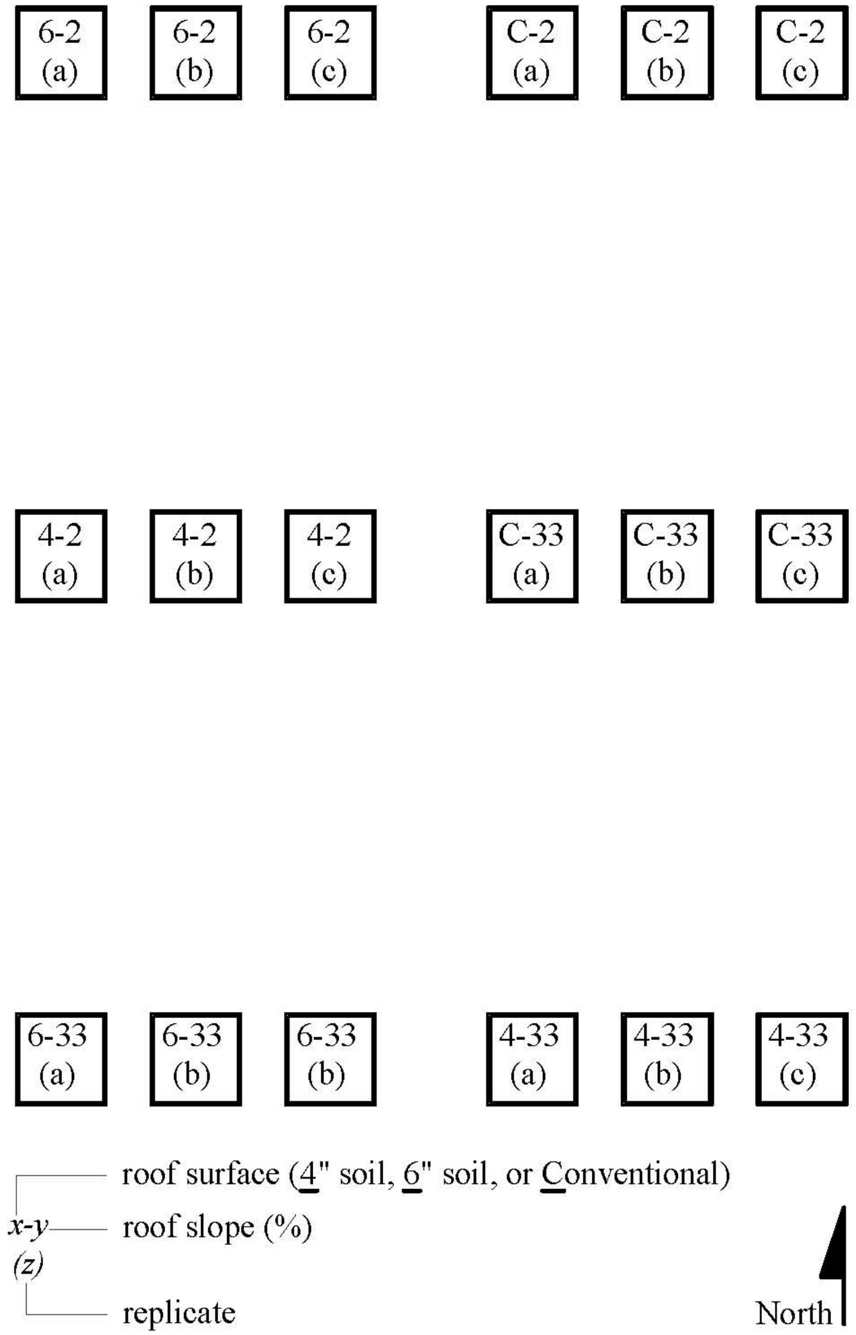
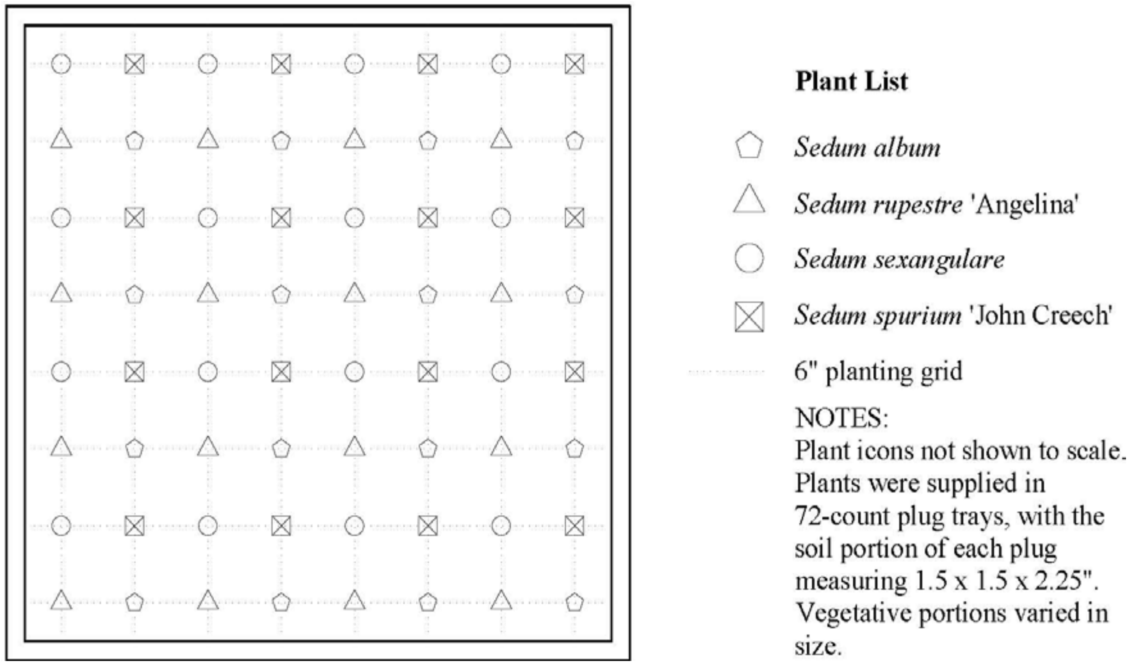


Figure 3.6 Plan view of study site showing placement of each treatment.

3.4 Plant Establishment

During the last week of July 2010, each platform was planted with four species of *Sedum* in a grid pattern at 6 in. on center (Figs. 3.7, 3.8). Each platform contained 16 individuals of each of the four species, totaling 64 plants per platform. The species planted were *Sedum album*, *Sedum rupestre* ‘Angelina,’ *Sedum sexangulare*, and *Sedum spurium* ‘John Creech’ (Fig. 3.9). *Sedum album* and *Sedum sexangulare* were identified by researchers at North Carolina State University as being suitable for green roofs in the Southeastern United States (Moran 2004). *Sedum rupestre* ‘Angelina’ and *Sedum spurium* ‘John Creech’ were recommended by Nashville Natives (Fairview, TN, www.nashvillenatives.com) as being suitable for the Southeastern region. The plants were supplied in 72-count plug trays, with each plug measuring 1.5 x 1.5 x 2.25 in. Plants were irrigated as needed for a period of approximately six weeks after planting. At commencement of data collection on September 15, 2010, all supplemental irrigation was discontinued, with the exception of three dates in June 2011 during an extended period of unseasonably hot, dry weather. All roof platforms were irrigated on June 6 and June 11, 2011. On June 8, 2011 only 33% sloped roof platforms were irrigated.

Figure 3.7	View of newly-planted roof platform with 6 in. planting grid.



NOTES:
Plant icons not shown to scale. Plants were supplied in 72-count plug trays, with the soil portion of each plug measuring 1.5 x 1.5 x 2.25". Vegetative portions varied in size.

Figure 3.8 Planting plan for all roof platforms.

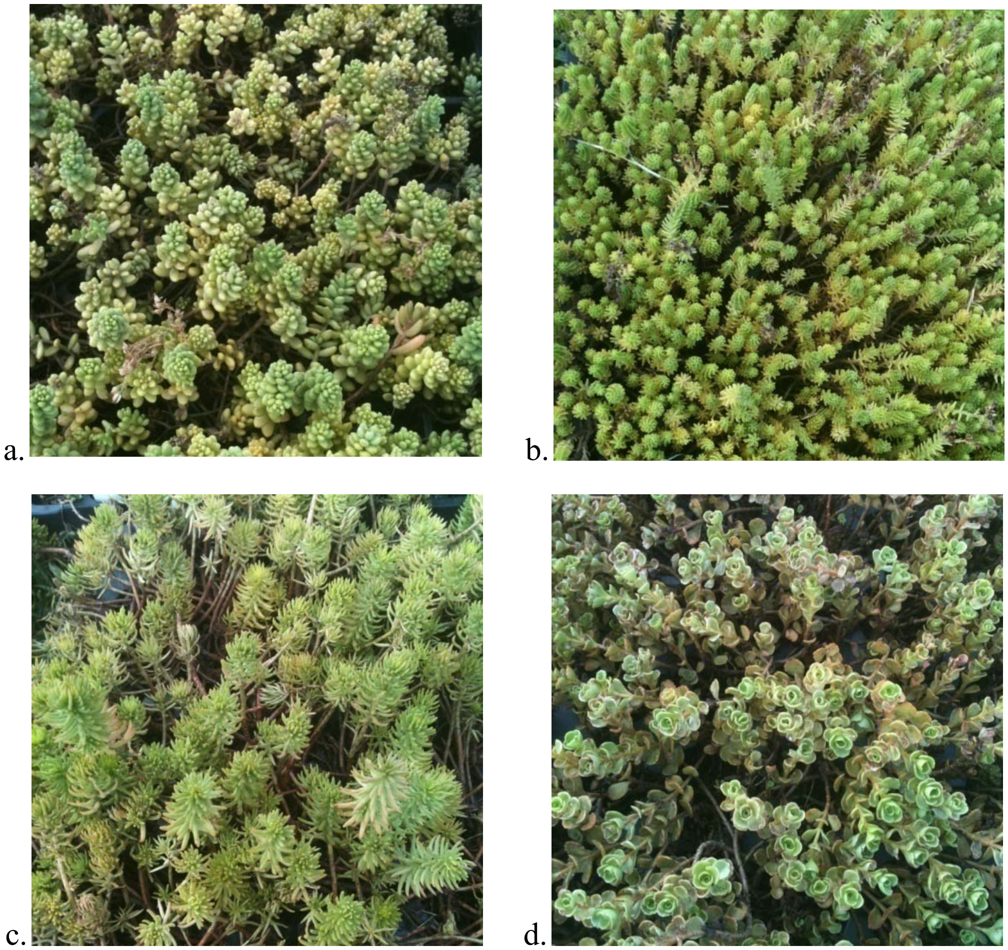


Figure 3.9 Four species planted on experimental green roof platforms. (a) *Sedum album,* (b) *Sedum sexangulare,* (c) *Sedum rupestre* "Angelina," (d) *Sedum spurium* "John Creech."

3.5 Data Collection and Analysis

Each platform was outfitted with a gutter system that routed all runoff into a 17-gallon plastic collection container (Fig. 3.10). The tare, or un-laden weight of each container was determined prior to the initiation of the study by suspending the empty container from a professional digital hanging scale (*PesolaPHS200,* Forestry Suppliers, Jackson, MS), with a precision level of ± 0.2 lbs. After each rain event, all containers were individually weighed using the professional digital hanging scale. The weight of each individual container was then subtracted from its tare weight to determine the overall weight of the water present in the container (Retzlaff et al. 2008). Using the formula,

$$\text{Volume (gallons)} = \frac{\text{Weight of water (lbs)}}{8.3378,} \tag{3.1}$$

with 8.3378 being the specific weight in pounds of one gallon of water at 60° F (mean annual temperature at study site), water weight was converted to volume. Percent retention per rain event for each module was then calculated based on total precipitation data collected in an on-site rain gauge (*All Weather Rain Gauge RG-202AW,* Productive Alternatives, Fergus Falls, MN) (Fig. 3.11) and the effective horizontal surface area of each roof platform (16 ft^2 for 2% sloped roofs and 15.23 ft^2 for 33% sloped roofs). Stormwater quantity data was collected continuously for 10.5 months, September 15, 2010 to July 31, 2011. Retention data from the conventionally-surfaced control roofs was not used due to flaws in the control roof design (no side walls) that allowed runoff to escape collection, and therefore retention to be overestimated. Any rain events separated by twelve or more hours were classified as individual events (Van Woert et al. 2005; Getter, Rowe, and Andresen 2007;USEPA 2009). Prior to analysis, rain events were categorized by rainfall event size as being small (<0.3899 in.), medium (0.39-0.6899 in.), or large (0.69-2.00 in.). The parameters of these categories were based on obtaining equal (or near equal) sample sizes for each category. Kolmogorov-Smirnov and Levene’s tests prior to analysis indicated a non-normal distribution of the dataset and a slight departure from homogeneity of variance, so a more stringent alpha level ($\alpha = 0.025$) was chosen for all statistical tests (Gamst, Meyers, and Guarino 2008; Keppel and Wickens 2004). A *t*-test was conducted to compare mean rainfall per event to mean runoff depth per event from green roof platforms (Hathaway, Jennings, and Hunt 2008).

Mean retention data for all rain events as a percentage of total precipitation for each rain event were analyzed with an ANOVA model, with roof slope, media depth, and rainfall category as fixed effects (Van Woert et al. 2005; Getter, Rowe, and Andresen 2007; Underwood 1997). A post-hoc Tukey HSD test was performed to determine significant differences between rainfall categories. An additional ANOVA model with roof treatment and rain category as fixed effects was used to directly compare individual treatments, and a post-hoc Tukey HSD test was used to identify where the differences occurred. All data analyses were conducted using SPSS version 19.0.

Figure 3.10 Stormwater runoff collection system.

Figure 3.11 On-site rain gauge attached to roof platform.

CHAPTER IV

RESULTS

Fifty rain events with an overall precipitation amount of 45.20 inches were recorded at the study site during the 10.5 month monitoring period. Seven rain events were not included in the analysis due to the overflowing of collection containers on six occasions and the dislodging of collection containers from gutter connections by wind on one occasion. Forty-three rain events, all representing rains equal to or less than 2.0 inches, were included in the analysis. These 43 events amounted to a total of 25.51 inches (56.44% of total rainfall for the study period). Of the 43 events analyzed, there were 15 small (<0.3899 in.), 14 medium (0.39-0.6899 in.), and 14 large (0.69-2.00 in.) rain events. Collected rainfall was 5.18 inches below the normal mean rainfall for this period (Fig. 4.1).

Runoff depth per rain event from green roof platforms was significantly less than rainfall depth per rain event over the course of the entire study period ($p < 0.025$) (Fig. 4.2, Table 4.1). Overall, green roof platforms retained 61.48% of rainfall for events of 2.0 inches or less.

Separating rainfall into distinct categories revealed 86.30% retention during small (<0.3899 in.), 65.08% during medium (0.39-0.6899 in.), and 31.28% during large (0.69-2.00 in.) rain events. The lowest retention observed across treatments in a single rain event was 8.19%, occurring during a 1.05-inch rain event on April 27, 2011. All green roofs retained 100% of rainfall on six separate occasions in which rainfall was 0.16 inches or less.

The main ANOVA model testing individual effects of soil depth and slope (Table 4.3) indicated that both factors were significant when rainfall events were not categorized by size. When split into individual rainfall categories, soil depth and slope were significant only for large events ($p<0.025$). Across both slopes (2%, 33%), the platforms with 4 inches of soil retained 57.80 % of rainfall and platforms with 6 inches retained 65.15% (Fig. 4.3, Table 4.2). Considered across both soil depths, 2% sloped roofs retained 65.24% of measured rainfall and the 33% sloped roofs retained 57.72%.

As shown in Table 4.2, when treatments were considered individually, the 2% - 6 inch depth platforms retained the most rainfall (70.5%), followed by the 2% - 4 inch (60.0%), 33% - 6 inch (59.8%), and 33% - 4 inch (55.6%) over all rain categories respectively. The highest retention was 93.6% on platforms with 2% slope and 6 inches of soil during small (<0.3899 in.) rain events. The lowest mean retention was 24.1% on the 33% - 4 inch platforms during large (0.69-2.00 in.) rain events. The lowest retention observed on an individual treatment in a single rain event was 3.88%, occurring on 33% - 4 inch platforms during a 1.05 inch rain event on April 27, 2011. One-hundred percent retention occurred thirty-six times across individual treatments.

The ANOVA model (Table 4.4) and post-hoc Tukey HSD test (Fig. 4.3) directly comparing treatments showed the difference between 2% - 6 inch and 33% – 4 inch platforms to be statistically significant when rainfall events were not categorized ($p = 0.003$). When split into individual rainfall categories, the difference between 2% - 6 inch and 33% – 4 inch was significant only for large events ($p<0.025$). The remaining treatments did not prove to differ statistically within rainfall categories.

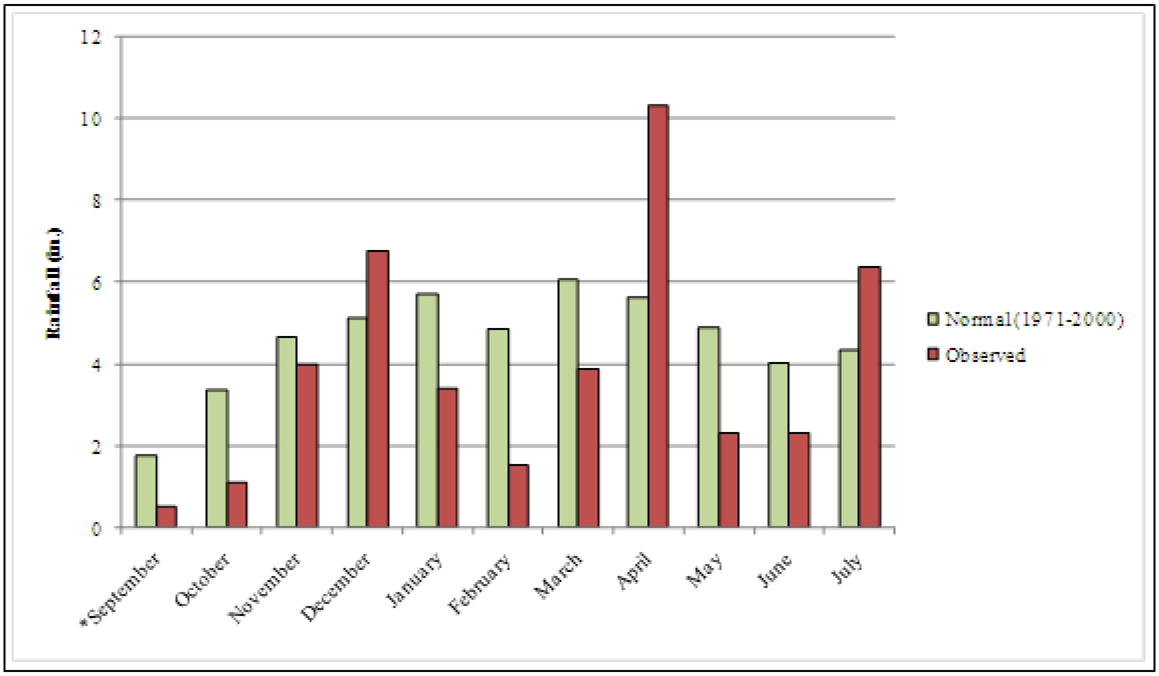


Figure 4.1 Normal and Observed Rainfall for Study Period. *Level depicted for normal rainfall in September was prorated to reflect data collection for 0.5 month.

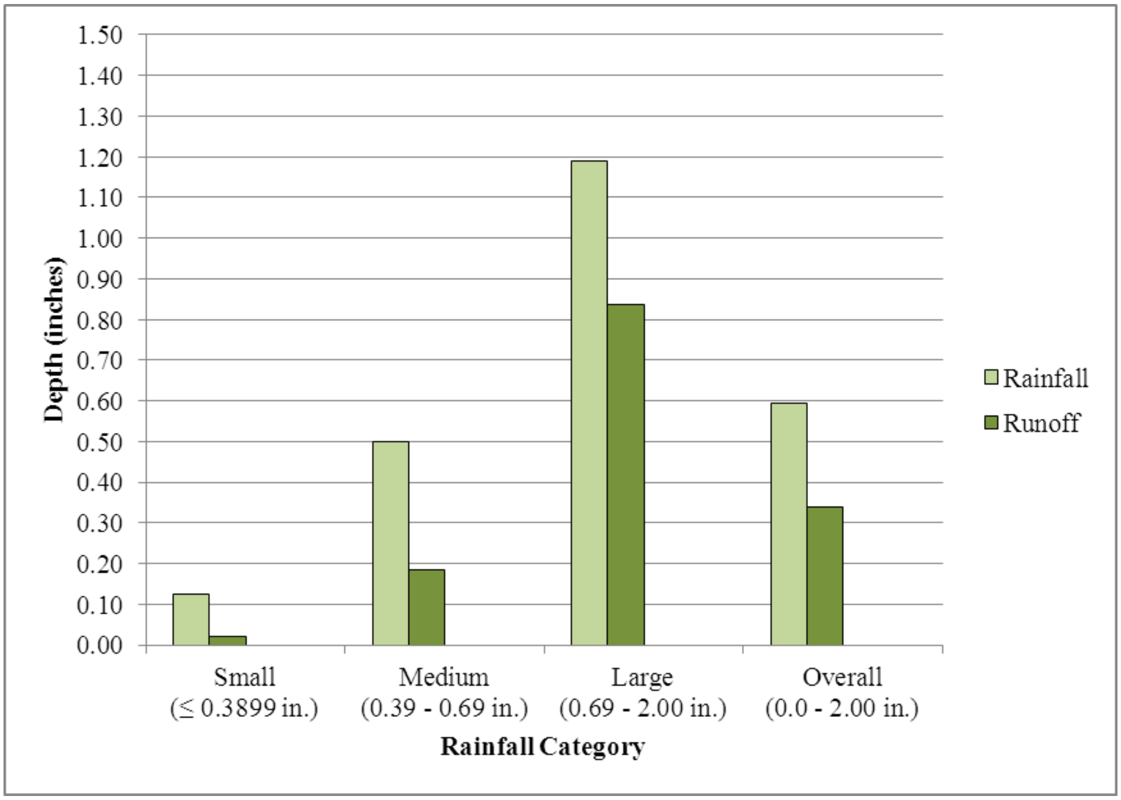


Figure 4.2 Mean rainfall depth vs. runoff depthfrom green roof platforms in respective categories for all measured rainfall events during 10.5-month study period. (small, n=60; medium, n=56; large, n=56).

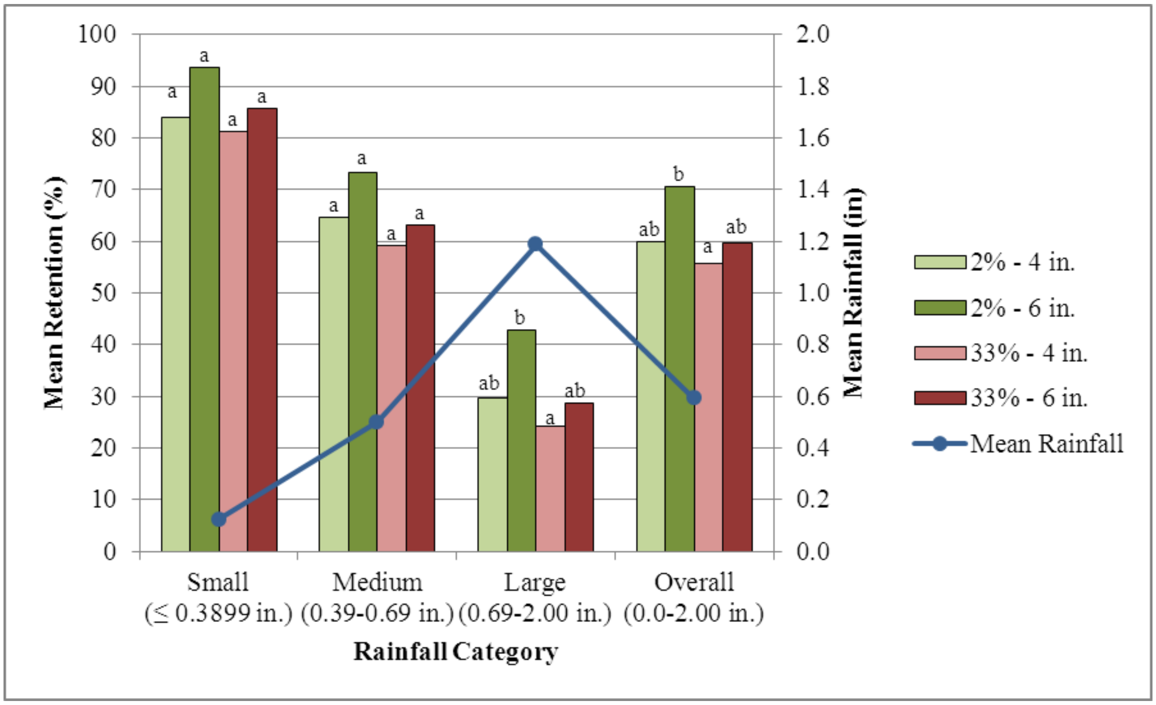
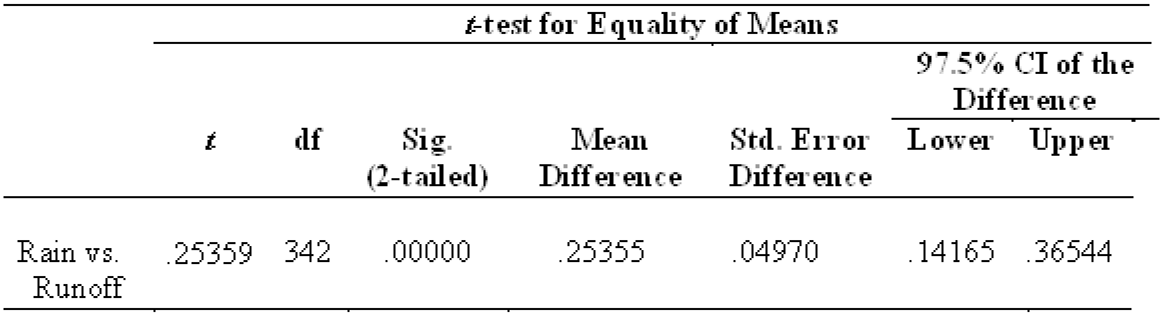


Figure 4.3 Mean percentage retention per rainfall event for all events up to 2.0 inches during the period September 15, 2010 to July 31, 2011. Data excludes any events with rainfall over 2.0 inches, as rainfalls over this amount overwhelmed the data-collection system. Individual events were categorized as small (<0.3899”, n=60), medium (0.39-0.6899”, n=56), large (0.69-2.00”, n=56), and overall (≤2.00”, N=172). Mean rainfall depth refers to mean within category. Letters above bars represent mean separation (p<0.025) between treatments within each rain category determined by Tukey’s HSD (bars sharing letters are not statistically different).

Table 4.1 Table for *t*-test comparing mean rainfall depth (in.) and mean runoff depth (in.) per rain event for all events of 2.0” or less over the 10.5-month period (15 Sep. 2010 to 31 Jul. 2011) from four roof platform treatments replicated three times.



	t-test for Equality of Means						
						97.5% CI of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Rain vs. Runoff	.25359	342	.00000	.25355	.04970	.14165	.36544

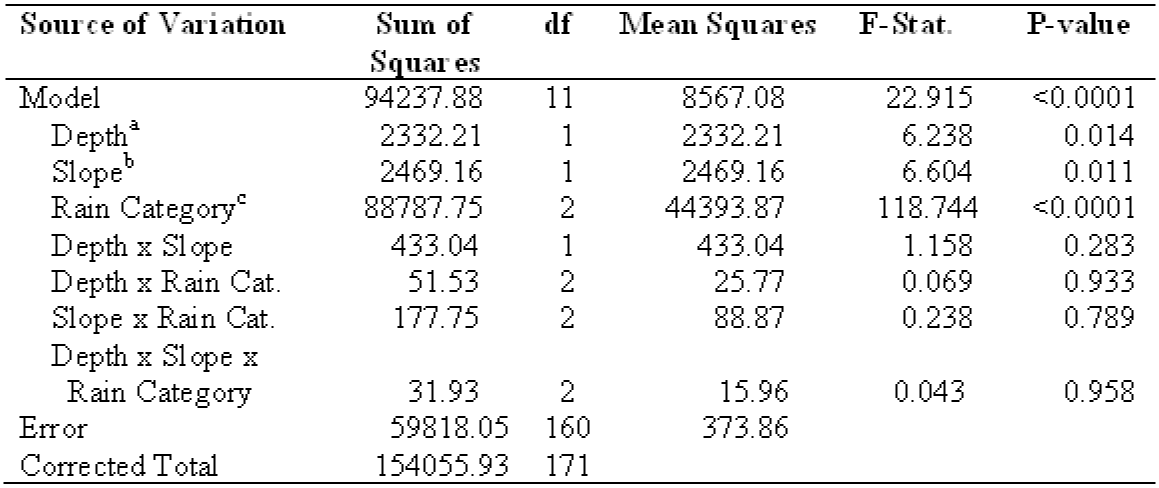
Table 4.2 Mean percentage ± one standard deviation of rainfall retention per rain event over the 10.5-month period (15 Sep. 2010 to 31 Jul. 2011) from four green roof platform treatments replicated three times.

Treatment†	**Small‡**	**Medium**	**Large**	**Overall**
	%	%	%	%
2% - 4”	84.0 ± 25.4	64.7 ± 23.9	29.6 ± 14.7	60.0 ± 31.3
2% - 6”	93.6 ± 15.7	73.4 ± 22.2	42.9 ± 13.1	70.5 ± 27.1
33% - 4”	81.2 ± 26.0	59.1 ± 16.8	24.1 ± 11.4	55.6 ± 30.4
33% - 6”	85.8 ± 23.4	63.2 ± 17.5	28.6 ± 14.0	59.8 ± 30.1

† Value denotes retention from roof platforms set at 2% slope with conventional roof surface (2% - Control), 2% slope with 4” of media (2% - 4”), 2 % slope with 6” of media (2% - 6”), 33.3% slope with conventional roof surface (33% - Control), 33.3% slope with 4” media (33% - 4”), and 33.3% slope with 6” media (33% - 6”).

‡ Rainfall categories are small (≤ 0.3899”) (n=60), medium (0.39 - 0.6899”) (n=56), large (> 0.69-2.00”) (n=56), and overall (N=172).

Table 4.3 ANOVA table for rainfall retention for events of 2.0” or less over the 10.5-month period (15 Sep. 2010 to 31 Jul. 2011) from four roof platform treatments replicated three times. Soil depth, slope, and rain category.



Source of Variation	Sum of Squares	df	Mean Squares	F-Stat.	P-value
Model	94237.88	11	8567.08	22.915	<0.0001
Depth[a]	2332.21	1	2332.21	6.238	0.014
Slope[b]	2469.16	1	2469.16	6.604	0.011
Rain Category[c]	88787.75	2	44393.87	118.744	<0.0001
Depth x Slope	433.04	1	433.04	1.158	0.283
Depth x Rain Cat.	51.53	2	25.77	0.069	0.933
Slope x Rain Cat.	177.75	2	88.87	0.238	0.789
Depth x Slope x Rain Category	31.93	2	15.96	0.043	0.958
Error	59818.05	160	373.86		
Corrected Total	154055.93	171			

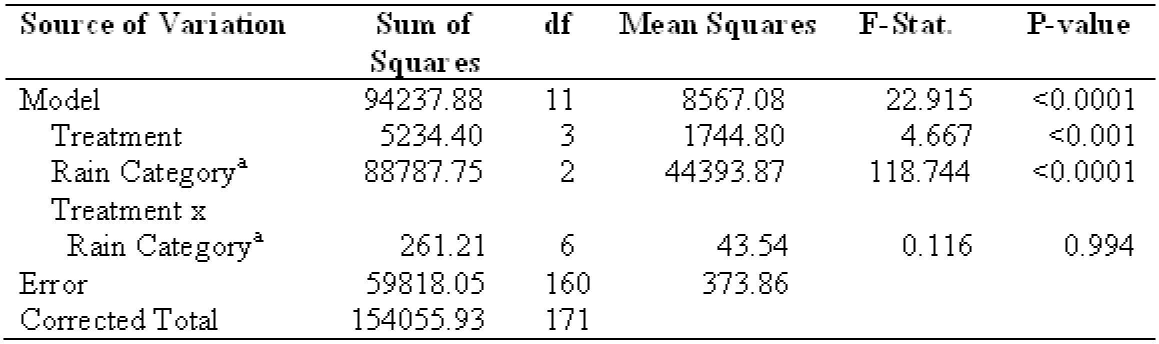
Retention is the dependent variable. Soil depth, roof slope, and rain category are independent variables

[a] Vegetated roof platforms at 4" and 6" soil depths.

[b] Vegetated roof platforms at 2% and 33% slopes.

[c] Rain event categories are small(≤0.3899") (n=60), medium (0.39-0.6899") (n=56), large (>0.69-2.00") (n=56), and overall (N=172).

Table 4.4 ANOVA table for rainfall retention for events of 2.0” or less over the 10.5-month period (15 Sep. 2010 to 31 Jul. 2011) from four roof platform treatments replicated three times. Treatment and rain category.



Source of Variation	Sum of Squares	df	Mean Squares	F-Stat.	P-value
Model	94237.88	11	8567.08	22.915	<0.0001
Treatment	5234.40	3	1744.80	4.667	<0.001
Rain Category[a]	88787.75	2	44393.87	118.744	<0.0001
Treatment x Rain Category[a]	261.21	6	43.54	0.116	0.994
Error	59818.05	160	373.86		
Corrected Total	154055.93	171			

Retention is the dependent variable. Roof treatment and rain category are independent variables

[a] Rain event categories are small (≤0.3899") (n=60), medium (0.39-0.6899") (n=56), large (>0.69-2.00") (n=56), and overall (N=172).

CHAPTER V

DISCUSSION AND CONCLUSION

5.1 Introduction

This chapter reintroduces the purpose of the study and the methods used to accomplish it. Following this is a thorough description and examination of the limitations of the study. Next, the results are discussed in the context of related research. Then suggestions for further research are given. The chapter concludes with a brief consideration of the implications and applications this study has for landscape architecture.

5.2 Review of Study Purpose and Methodology

As stated in Chapter 1, this thesis seeks to establish baseline stormwater performance data for extensive green roofs in Mississippi's climate. Specifically, the study's purpose is to determine what effect the greening of a rooftop has on stormwater retention, what effect soil depth has on retention, and what effect roof slope has on retention.

In order to determine the effects of rooftop greening, soil depth, and roof slope, a controlled experiment was conducted utilizing 18 small-scale roof platforms. Runoff was collected from these roof platforms for each rain event from September 15, 2010 to July 31, 2011. Retention data was then statistically analyzed to determine the effect of the individual design variables and of their combination within treatments.

5.3 Limitations

It is important that any discussion of the results of this study is conducted in light of its limitations. What follows is a description of those limitations.

First, the findings of this study represent rain events of 2.0 in. or less. As stated earlier, this accounted for 43 of 50 total rain events and 56.44% of total rainfall depth for the study period. Had all rain events been included, retention percentages would likely have been considerably lower. This inability to capture all rainfall was dictated by the combination of the size of roof platforms and the selected collection system. Roof platforms were sized and constructed with the idea that they would be used for future green roof studies; the intent was to make them as large as possible, yet small enough to be moved if necessary. The method of monitoring via collection in containers was selected based on financial restrictions, and the size of the containers was limited by what could reasonably be lifted to weigh. Furthermore, this collection method limited data and analysis to rainfall depth and retention; no time-dependent information was gathered that would have allowed calculation of any effects the green roofs might have had on the detention of runoff.

Second, an error was made in the design and construction of the conventional roof platforms that did not allow direct comparison of conventional roof platforms with green roof platforms. These conventionally-surfaced platforms were constructed without the 8-in. sidewalls that were included on the green roof platforms. It was believed that the roof slope would exert enough influence on the direction of the runoff as to route it all into the collection system. This assumption proved to be false, as water was observed escaping the sides of the roof platforms. Though an attempt was made to ameliorate this problem by adding 2-in. sheet-metal sides, this too proved insufficient, as water was observed splashing over the short sidewalls. As a result of this error, data collected from the conventionally surfaced roof platforms was deemed unreliable and was not included in the analysis.

Third, the length of the study period was only 10.5 months; no data was collected during August or the first half of September. The majority of green roof studies reviewed in this thesis were conducted over of a period of at least one year, allowing insight into the variations seen throughout the seasons. Therefore, results may only reasonably be applicable to the period from September 15 to July 31.

Fourth, the entire study period was conducted under what could be considered the establishment period of the green roofs, and results are applicable for this period only. Though plant cover was not calculated in this study, the highest estimated plant coverage of any of the green roofs was approximately 75% and the lowest approximately 30% at the end of the data collection period. Based on the literature, it is reasonable to expect that different retention percentages could be found as plants become fully established and green roofs achieve full coverage.

Finally, the results of this study are also limited by the fact that the experiment was conducted on small-scale simulated roof platforms rather than full-scale roofs. While the roof platforms were constructed in a manner consistent with typical full-scale extensive green roofs, several factors could have affected their performance. First, the small scale roofs contain a higher proportion of edge-to-interior area than would a larger, full-scale roof. This higher proportion of edge could conceivably affect retention of the green roof due to the drying effect imposed by the higher degree of exposure at the edges. Also, the roof platforms were situated 3.5 ft. aboveground-level. The low elevation could have reduced the amount of wind the platforms were exposed to, likely reducing soil evaporation rates. Moreover, the roof platforms were placed amidst a large expanse of pasture. Though no temperature measurements were taken, ambient temperatures were likely lower here than would be expected within an urbanized area.

5.4 Discussion of Results

What follows is a discussion of the findings in the context of the literature. Each topic is addressed in the same order as presented in the Results chapter. First is a discussion of green roof runoff depth vs. rainfall depth. After that, the individual effects of soil depth and slope is considered. Then, the comparison of individual treatments is explored. This section concludes with a general discussion of the results and factors that could have influenced the results.

It came as no surprise that runoff depth per event from green roof platforms was significantly less than rainfall depth per event over the entire study period ($p<0.001$). This is consistent with findings of Hathaway, Jennings, and Hunt (2008), which also found significant reductions in green roof runoff when directly compared to rainfall depth. Other studies found significant differences between green roof runoff depth and conventional roof runoff depth. Though that comparison was unable to be made in this study due to the flaw in the conventional roof platforms discussed above, it is likely that green roof retention would have been significantly greater than conventional roof retention, as the mean per event retention rate for the study period (61.48%) falls within the range (45-85.2%) found by others (Berghage et al. 2007; Mentens, Raes, and Hermy 2006; Getter, Rowe, and Andresen 2007; Carter and Rasmussen 2006).

It was hypothesized that increasing soil depth would increase retention for green roof platforms. As expected, green roofs with 6 in. soil retained significantly more rainfall than roofs with 4 in. soil (p=0.014). Though this difference was significant across all analyzed rain events, when rain events were categorized according to size, this difference was only significant for large events (p=0.016). This is somewhat different than findings by Van Woert et al. (2005) in which the difference in retention between soil depths was significant across all rain events, but only for light and medium rain events when categorized. It is possible that differences in rain event duration and intensity and/or antecedent soil moisture conditions partially account for this difference between the two studies (Villarreal and Bengtsson 2005; Stovin, Dunnett, and Hallam 2007). Though a complete array of data from rain events is not reported, Van Woert et al. (2005) recorded a total of 21.89 in. over 83 rain events during the 14-month study, resulting in a mean per rain event of 0.26 in. The mean rain event size for this study was considerably higher, at 0.59 in. However, the mean soil depth for this study was also considerably greater (5 in. vs. 1.6 in.) than those of Van Woert et al. (2005).

It was also hypothesized that increasing roof slope would decrease retention. This was shown to be the case, with 2% sloped roofs retaining significantly more rainfall than 33% sloped roofs across all rain events (p=0.011). When rain events were categorized, this difference was only significant during large rain events (p=0.008).This agrees with Getter, Rowe, and Andresen (2007), which found significant differences in retention between 2% and 25% sloped roofs across all rain events, but when categorized by size the difference was significant only in heavy rain events. However, results from the present study yielded considerably lower retention percentages overall than those of Getter, Rowe, and Andresen (2007) despite having much deeper soil depths.

In the direct comparison of varying treatments, across all rain events the 2% - 6 in. treatment retained significantly more water than the 33% - 4 in. treatment (p=0.003).

When rain events were categorized, this difference was only significant for large events (p=0.003). Though differences in observed means between other treatments is considerable (10.5% between 2% - 4 in. and 2% - 6 in.), these differences did not prove to be statistically significant. This is very similar to Van Woert et al. (2005), which saw significant differences between 2% - 1.4 in. and 6.5% - 2.4 in. roofs.

One prior assumption of this study was that though increasing slope may reduce retention, increasing soil depth might offset this. There was no statistical difference between 2% - 4 in. roofs and 33% - 6 in. roofs, and the observed means only differ by 0.2%. These results suggest that this prior assumption has some merit, and that increasing soil depth might offset the effect of increasing slope. Operating under the same assumption, Van Woert et al. (2005) found significant differences between 2% - 1.6 in. and 6.5% - 2.4 in. roofs, implying that this assumption did not hold. Perhaps the very small increase (0.8 in) in soil depth in the Van Woert et al. study was not enough to offset the effect of increased slope.

Differences in rainfall patterns likely explain some of this difference between the studies. Michigan, where the Van Woert et al. (2005) and Getter, Rowe, and Andresen (2007) studies were conducted, and the Mississippi State area have storms of the same relative intensity, yet storms in the Mississippi State area are much larger. For example, Michigan’s 100-year event is equal in magnitude to the Mississippi State area’s 2-year event (Cronshey 1986).

It is worth noting that within this study, though soil depth and roof slope were not statistically significant during small and medium rain events, there were considerable differences in the observed mean retention values for the two soil depths and two slopes during those respective rain events. This lack of statistical significance is liable to be at least partially attributable to the small sample sizes ($n \leq 15$) that result from rain events being categorized and partially attributable to factors within rain categories, such as antecedent dry weather period and rainfall intensity, which are not accounted for in the ANOVA models and which resulted in high error variances. Simply increasing the sample size (collecting data for a longer period) would likely yield a higher number of significant differences among factors, as would collecting and accounting for more finely-grained details pertaining to rainfall. So, the lack of statistical significance of soil depth and slope during small and medium events does not mean that these factors are not important, or do not affect retention.

These factors should be considered for reasons other than the immediate effect they might have on stormwater retention. Soil depth, for instance, affects which species can survive and prosper on a green roof (Dunnett, Nagase, and Hallam 2008; Getter and Rowe 2009), and healthy vegetation can in-turn lead to higher soil water-retention properties as a green roof ages (Getter, Rowe, and Andresen 2007). Sloped green roofs may initially be chosen to increase aesthetic appeal or to reduce heat gain (Weiler and Scholz-Barth 2009), but slope and slope orientation affect plant growth (Martin and Hinkley 2007), which ultimately influences water retention.

5.5 Conclusions

The results of this experiment indicate that green roofs can serve as an effective tool for retaining stormwater during rain events of up to 2.0 inches in a humid, subtropical climate. The study also shows that soil depth and slope usually matter when considering stormwater retention. That is, retention values will tend to increase as soil depth increases and decrease as roof slope increases, but this effect will vary with rain event size. These results are applicable to Mississippi and other areas with similar climates.

5.6 Suggestions for Further Research

The current study should be improved upon, and the effects of soil depth and slope on retention should continue to be studied in Mississippi's climate. Improvements, most of which were implied by the discussion of the study's limitations above, should focus on obtaining more finely detailed information on rainfall and runoff from roof platforms. First, conventional roof platforms should be upgraded in order to be able to make comparisons between conventional roofs and green roofs under local conditions. Second, a monitoring system that is able to determine runoff volume from all rain events is needed, and this monitoring system should have the capability of precisely determining when a rain event began, how long it lasted, when runoff began, when runoff volume peaked, when runoff ended, and the length of time in between rain events. Armed with this information, researchers should be able to draw very strong conclusions about the performance of green roofs and the effects of soil depth and slope in Mississippi's climate. This should ultimately lead to the development of a curve number for green roofs, which will aid in the decision-making power of those intending to specify green roofs based on their stormwater performance in Mississippi's, or very similar climates.

Design variables beyond soil depth and slope should also be studied for their effect on stormwater retention. Simmons (2008) noted dramatic differences in retention between green roofs that contained different drainage and retention layers, and these differences were sometimes greater than differences between conventional roofs and green roofs. And as vegetation has been shown to affect retention, research should be conducted on specific plant materials suitable for Mississippi's climate that could help to optimize the green roofs' stormwater performance. These ideas will certainly additional layers of complexity to an already complex equation, but understanding these design variables will ultimately enable designers and policy-makers to make sound decisions regarding the use of green roofs to mitigate stormwater runoff.

These and other green roof design variables should also be studied for their effect on runoff quality. The literature suggests that water quality of runoff from green roofs is primarily affected by soil composition and fertilizer applications and that it varies seasonally, with higher export of nutrients during warmer periods. Conducting research in Mississippi's climate to identify optimal soil mixes and proper management techniques for satisfying the sometimes seemingly competing goals of plant growth and water quality could potentially be of very high value.

5.7 Implications and Applications for Landscape Architecture

As awareness of the negative effects of urbanization on natural systems and its consequent effects on human health and well-being increases, methods to minimize the impact of human settlements on natural processes will likely become more common. These methods which embody nature's pattern of the development of systems of interrelated elements operating together to perform a wide variety of ecosystem services include systems such as green roofs.

The findings of this study on green roofs are potentially of great value to landscape architects and others seeking to design and implement extensive green roofs to reduce stormwater runoff in Mississippi. Knowing how soil depth and roof slope will affect retention in this climate will give designers the ability to use green roofs to help manage stormwater from buildings with varying slopes. While the data presented here shows that retention can be maximized with greater soil depth and lower slope, it also shows that the lower retention percentages associated with roofs of greater slope can be offset with increased soil depth. The latter finding is arguably the most meaningful, because it is unlikely that green roofs will be implemented solely on the basis of one beneficial attribute.

In fact, green roof projects are typically designed in order to satisfy a number of objectives specified by, or developed in concert with stakeholders (Snodgrass and McIntyre 2010). Though this thesis has focused on one particular beneficial aspect of green roofs, there are many reasons that their implementation might be considered on an individual project or on a wider scale. Several of the more prominent benefits and objectives of green roofs projects such as the reduction of energy use and the urban heat island effect, increased life span of waterproof membranes, and mitigation of stormwater runoff were highlighted in the literature review. Stakeholders may also be interested in other benefits including reduction in air and noise pollution, increased biodiversity and carbon sequestration, wind buffering, fire protection, potential credits toward LEED certification, increased aesthetic value, or simply an enhanced reputation in the community due to a perception of the owner’s commitment to the environment (Getter and Rowe 2006; Snodgrass and McIntyre 2010).

Though the results of this study indicate that more stormwater can be retained on roofs with a lower slope at a given soil depth, landscape architects or other professionals working on green roof projects and seeking to optimize these living systems’ benefits should not necessarily choose a low slope over a greater one. The goal should be to achieve the best balance between the various benefits afforded by the green roof based on the project objectives and budget. Optimizing these benefits will often result in minor compromises on acceptable performance level for any single beneficial attribute. For instance, a higher-sloped green roof, though requiring greater a soil depth to achieve a certain level of stormwater retention, will be more visible from the ground-plane. This increased visibility can enhance built structures, either transforming them into central foci of the landscape or allowing them to visually blend with other natural elements (Dunnett and Clayden 2007). And any increased visibility of green roofs is liable increase public awareness and curiosity about green roofs. In fact, visual prominence of a green roof can contribute greatly to what Echols and Pennypacker (2008) call "artful rainwater design," an approach to design that treats stormwater as a highly-valuable aesthetic and educational amenity, and one which provides "landscape architects the opportunity to be good stewards of land and water while creating meaningful places for people to experience."

Green roofs, being relatively complex systems requiring a broad range of knowledge to successfully implement and maintain, will most certainly require collaborative teams of architects, engineers, horticulturists, contractors, and landscape architects to successfully create. Landscape architects, being highly-attuned to the effects of site decisions on both on-site and off-site conditions and good synthesizers of broad ranges of information, are well-poised to become leaders of these collaborative teams. But, in order for these teams to effectively maximize the environmental, economic, and social benefits offered by green roofs, the local performance of these systems must be understood.

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APPENDIX A

RETENTION DATA FOR EACH TREATMENT REPLICATION FOR ALL OBSERVED RAIN EVENTS

Table A.1 Treatment: 2% - 4 in.

		Retention %			
Date	**Rain (in)**	**4-2(a)**	**4-2(b)**	**4-2(c)**	**Treatment Mean**
09/25/10	0.08	100.00	100.00	100.00	100.00
09/26/10	0.43	69.24	69.24	65.88	68.12
10/12/10	0.18	100.00	100.00	100.00	100.00
10/23/10	0.39	70.40	73.48	70.40	71.43
10/26/10	0.52	41.26	38.49	39.41	39.72
11/02/10	1.29	25.05	21.70	23.56	23.44
11/13/10	0.38	87.98	81.65	82.28	83.97
11/17/10	0.95	28.86	27.34	17.98	24.73
11/23/10	0.80	25.45	27.55	20.64	24.54
11/25/10	0.57	54.43	55.28	54.01	54.57
12/01/10	3.18	*	*	*	*
12/11/10	0.69	48.76	39.35	42.49	43.53
12/15/10	0.09	100.00	100.00	100.00	100.00
12/16/10	0.07	41.59	27.85	65.64	45.03
12/25/10	0.20	65.13	90.38	92.79	82.76
12/31/10	2.55	*	*	*	*
01/05/11	0.05	100.00	100.00	100.00	100.00
01/09/11	0.39	99.38	98.15	98.77	98.77
01/20/11	0.11	30.04	60.65	58.46	49.71
01/24/11	0.01	100.00	100.00	100.00	100.00
01/25/11	1.81	16.56	15.36	17.09	16.34
01/31/11	1.04	23.69	22.30	31.78	25.92
02/04/11	0.59	58.42	21.74	43.34	41.17
02/09/11	0.18	57.25	42.55	55.91	51.90
02/24/11	0.75	70.18	58.63	65.69	64.83

Table A.1 (continued)

		Retention %			
Date	**Rain (in)**	**4-2(a)**	**4-2(b)**	**4-2(c)**	**Treatment Mean**
02/25/11	0.01	100.00	100.00	100.00	100.00
03/04/11	1.47	32.60	28.83	20.16	27.20
03/08/11	0.73	42.02	51.57	44.98	46.19
03/14/11	1.08	27.63	18.50	18.72	21.62
03/27/11	0.16	100.00	100.00	100.00	100.00
03/29/11	0.42	98.28	98.28	97.14	97.90
04/04/11	2.01	*	*	*	*
04/11/11	0.14	100.00	100.00	98.28	99.43
04/15/11	3.99	*	*	*	*
04/20/11	3.11	*	*	*	*
04/27/11	1.05	1.51	6.32	3.80	3.88
05/03/11	0.52	72.25	67.16	68.09	69.17
05/13/11	0.28	100.00	100.00	100.00	100.00
05/26/11	1.50	38.11	34.75	36.03	36.30
06/13/11	2.14	*	*	*	*
06/16/11	0.59	53.94	55.16	54.75	54.62
06/21/11	1.48	31.43	32.40	30.86	31.56
06/22/11	0.26	23.23	45.43	25.08	31.24
06/23/11	0.04	100.00	100.00	100.00	100.00
06/28/11	0.56	98.28	98.71	97.85	98.28
07/13/11	2.71	*	*	*	*
07/14/11	0.68	17.24	25.73	26.08	23.02
07/17/11	0.47	62.65	60.60	58.04	60.43
07/21/11	2.00	14.86	22.20	34.34	23.80
07/25/11	0.50	38.43	36.03	57.19	43.88

Table A.2 Treatment: 2% - 6 in.

		Retention %			
Date	**Rain (in)**	**6-2(a)**	**6-2(b)**	**6-2(c)**	**Treatment Mean**
09/25/10	0.08	100.00	100.00	100.00	100.00
09/26/10	0.43	70.36	73.15	73.15	72.22
10/12/10	0.18	100.00	100.00	100.00	100.00
10/23/10	0.39	85.82	87.67	79.65	84.38
10/26/10	0.52	61.61	56.53	59.76	59.30
11/02/10	1.29	51.71	35.22	42.02	42.98
11/13/10	0.38	99.37	99.37	88.61	95.78
11/17/10	0.95	68.36	34.18	56.20	52.91
11/23/10	0.80	44.69	31.46	32.06	36.07
11/25/10	0.57	46.42	45.99	49.79	47.40
12/01/10	3.18	*	*	*	*
12/11/10	0.69	55.73	44.93	53.64	51.44
12/15/10	0.09	100.00	100.00	100.00	100.00
12/16/10	0.07	38.16	14.11	82.82	45.03
12/25/10	0.20	100.00	100.00	100.00	100.00
12/31/10	2.55	*	*	*	*
01/05/11	0.05	100.00	100.00	100.00	100.00
01/09/11	0.39	100.00	100.00	100.00	100.00
01/20/11	0.11	100.00	97.81	80.32	92.71
01/24/11	0.01	100.00	100.00	100.00	100.00
01/25/11	1.81	36.09	18.68	22.27	25.68
01/31/11	1.04	59.07	47.04	30.16	45.43
02/04/11	0.59	85.33	55.57	60.87	67.25
02/09/11	0.18	100.00	100.00	100.00	100.00
02/24/11	0.75	69.54	82.04	59.28	70.29
02/25/11	0.01	100.00	100.00	100.00	100.00
03/04/11	1.47	57.46	55.34	36.36	49.72

Table A.2 (continued)

		Retention %			
Date	**Rain (in)**	**6-2(a)**	**6-2(b)**	**6-2(c)**	**Treatment Mean**
03/08/11	0.73	54.21	51.90	38.39	48.17
03/14/11	1.08	44.11	28.74	30.30	34.38
03/27/11	0.16	100.00	100.00	100.00	100.00
03/29/11	0.42	98.28	96.56	97.14	97.33
04/04/11	2.01	*	*	*	*
04/11/11	0.14	94.85	98.28	98.28	97.14
04/15/11	3.99	*	*	*	*
04/20/11	3.11	*	*	*	*
04/27/11	1.05	12.05	14.80	19.61	15.48
05/03/11	0.52	87.51	81.04	80.11	82.89
05/13/11	0.28	100.00	100.00	99.14	99.71
05/26/11	1.50	47.57	41.64	42.12	43.78
06/13/11	2.14	*	*	*	*
06/16/11	0.59	75.14	73.50	59.65	69.43
06/21/11	1.48	56.29	55.64	31.26	47.73
06/22/11	0.26	75.03	81.50	50.05	68.86
06/23/11	0.04	100.00	100.00	100.00	100.00
06/28/11	0.56	100.00	100.00	100.00	100.00
07/13/11	2.71	*	*	*	*
07/14/11	0.68	49.43	38.81	35.99	41.41
07/17/11	0.47	84.14	78.51	73.90	78.85
07/21/11	2.00	39.76	27.13	40.96	35.95
07/25/11	0.50	36.03	32.18	26.89	31.70

Table A.3 Treatment: 33% - 4 in.

		Retention %			
Date	**Rain (in)**	**4-33(a)**	**4-33(b)**	**4-33(c)**	**Treatment Mean**
09/25/10	0.08	72.94	69.94	81.96	74.95
09/26/10	0.43	68.12	56.93	64.76	63.27
10/12/10	0.18	82.63	61.25	77.29	73.72
10/23/10	0.39	71.63	69.78	71.02	70.81
10/26/10	0.52	55.60	52.83	56.99	55.14
11/02/10	1.29	34.75	29.34	39.22	34.44
11/13/10	0.38	68.99	61.39	71.52	67.30
11/17/10	0.95	46.33	28.86	48.61	41.27
11/23/10	0.80	20.94	19.73	23.04	21.24
11/25/10	0.57	61.61	54.85	64.14	60.20
12/01/10	3.18	*	*	*	*
12/11/10	0.69	43.54	43.88	45.63	44.35
12/15/10	0.09	100.00	100.00	100.00	100.00
12/16/10	0.07	62.21	31.29	75.95	56.48
12/25/10	0.20	100.00	100.00	100.00	100.00
12/31/10	2.55	*	*	*	*
01/05/11	0.05	100.00	100.00	100.00	100.00
01/09/11	0.39	86.43	79.65	93.22	86.43
01/20/11	0.11	32.22	25.66	56.27	38.05
01/24/11	0.01	100.00	100.00	100.00	100.00
01/25/11	1.81	23.33	20.01	24.66	22.67
01/31/11	1.04	13.75	10.97	12.82	12.51
02/04/11	0.59	47.82	49.05	44.97	47.28
02/09/11	0.18	63.93	61.25	62.59	62.59
02/24/11	0.75	37.47	33.94	28.17	33.20
02/25/11	0.01	100.00	100.00	100.00	100.00
03/04/11	1.47	19.51	17.87	17.87	18.42

Table A.3 (continued)

		Retention %			
Date	**Rain (in)**	**4-33(a)**	**4-33(b)**	**4-33(c)**	**Treatment Mean**
03/08/11	0.73	30.49	27.85	31.80	30.05
03/14/11	1.08	20.06	17.39	25.85	21.10
03/27/11	0.16	100.00	100.00	100.00	100.00
03/29/11	0.42	58.77	57.05	61.64	59.15
04/04/11	2.01	*	*	*	*
04/11/11	0.14	98.28	98.28	100.00	98.85
04/15/11	3.99	*	*	*	*
04/20/11	3.11	*	*	*	*
04/27/11	1.05	7.01	3.34	3.11	4.49
05/03/11	0.52	69.48	67.63	65.31	67.47
05/13/11	0.28	99.14	95.71	95.71	96.85
05/26/11	1.50	23.36	22.72	21.92	22.67
06/13/11	2.14	33.81	27.96	32.91	31.56
06/16/11	0.59	42.71	26.63	29.89	33.07
06/21/11	1.48	17.01	7.54	7.21	10.59
06/22/11	0.26	35.26	12.13	31.55	26.31
06/23/11	0.04	100.00	100.00	100.00	100.00
06/28/11	0.56	84.54	84.11	87.55	85.40
07/13/11	2.71	*	*	*	*
07/14/11	0.68	44.83	45.89	49.43	46.71
07/17/11	0.47	54.46	53.44	60.09	55.99
07/21/11	2.00	16.67	19.79	23.40	19.95
07/25/11	0.50	29.78	23.52	33.14	28.81

Table A.4 Treatment: 33% - 6 in.

Date	**Rain (in)**	**Retention %** **6-33(a)**	**6-33(b)**	**6-33(c)**	**Treatment Mean**
09/25/10	0.08	100.00	100.00	100.00	100.00
09/26/10	0.43	75.95	75.95	75.95	75.95
10/12/10	0.18	85.30	85.30	85.30	85.30
10/23/10	0.39	72.25	72.25	72.25	72.52
10/26/10	0.52	68.55	68.55	68.55	68.55
11/02/10	1.29	45.00	45.00	45.00	45.00
11/13/10	0.38	72.15	72.15	72.15	72.15
11/17/10	0.95	56.71	56.71	56.71	56.71
11/23/10	0.80	14.92	23.94	18.83	19.23
11/25/10	0.57	78.90	59.92	61.61	66.81
12/01/10	3.18	*	*	*	*
12/11/10	0.69	52.60	45.98	42.84	47.14
12/15/10	0.09	100.00	100.00	100.00	100.00
12/16/10	0.07	75.95	38.16	27.85	47.32
12/25/10	0.20	100.00	100.00	100.00	100.00
12/31/10	2.55	*	*	*	*
01/05/11	0.05	100.00	100.00	100.00	100.00
01/09/11	0.39	95.07	77.18	77.80	83.35
01/20/11	0.11	67.21	58.46	51.90	59.19
01/24/11	0.01	100.00	100.00	100.00	100.00
01/25/11	1.81	28.12	28.52	21.21	25.95
01/31/11	1.04	26.00	13.75	7.96	15.90
02/04/11	0.59	52.72	44.16	35.60	44.16
02/09/11	0.18	91.98	66.60	61.25	73.28
02/24/11	0.75	37.15	31.38	31.38	33.30
02/25/11	0.01	100.00	100.00	100.00	100.00
03/04/11	1.47	31.45	28.83	13.62	24.63

Table A.4 (continued)

		Retention %			
Date	**Rain (in)**	**6-33(a)**	**6-33(b)**	**6-33(c)**	**Treatment Mean**
03/08/11	0.73	42.35	35.76	29.83	35.98
03/14/11	1.08	20.73	19.61	18.50	19.61
03/27/11	0.16	100.00	100.00	100.00	100.00
03/29/11	0.42	57.05	65.07	57.05	59.73
04/04/11	2.01	*	*	*	*
04/11/11	0.14	93.13	100.00	94.85	95.99
04/15/11	3.99	*	*	*	*
04/20/11	3.11	*	*	*	*
04/27/11	1.05	13.42	5.40	7.92	8.92
05/03/11	0.52	66.70	80.11	69.48	72.10
05/13/11	0.28	96.56	100.00	99.14	98.57
05/26/11	1.50	24.80	31.54	33.78	30.04
06/13/11	2.14	38.19	37.07	26.73	33.99
06/16/11	0.59	27.04	28.26	31.11	28.80
06/21/11	1.48	10.79	12.74	9.65	11.06
06/22/11	0.26	25.08	32.48	24.15	27.23
06/23/11	0.04	100.00	100.00	100.00	100.00
06/28/11	0.56	85.83	88.83	90.98	88.55
07/13/11	2.71	*	*	*	*
07/14/11	0.68	56.85	53.67	47.66	52.73
07/17/11	0.47	63.16	63.67	66.74	64.52
07/21/11	2.00	26.41	29.78	25.09	27.09
07/25/11	0.50	40.36	26.89	36.99	34.75

APPENDIX B

SPSS OUTPUT FOR ALL STATISTICAL ANALYSES

B.1 Results for *t*-test comparing rainfall and runoff depth

Group Statistics

	Rain or Runoff	N	Mean	Std. Deviation	Std. Error Mean
Mean Depth (in)	Rain	172	.5933	.50315	.03836
	Runoff	172	.3397	.41439	.03160

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Mean Depth (in)	Equal variances assumed	4.066	.045	5.101	342
	Equal variances not assumed			5.101	329.881

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
Mean Depth (in)	Equal variances assumed	.00000	.25355	.04970
	Equal variances not assumed	.00000	.25355	.04970

Independent Samples Test

		t-test for Equality of Means	
		97.5% Confidence Interval of the Difference	
		Lower	Upper
Mean Depth (in)	Equal variances assumed	.14165	.36544
	Equal variances not assumed	.14163	.36546

B.2 ANOVA Model: Soil depth, roof slope, and rain category

B.2.1 All Rain Events

Between-Subjects Factors

		N
MediaDepth	4"	86
	6"	86
RoofSlope	2%	86
	33.3%	86
RainCategory	1	60
	2	56
	3	56

Tests of Between-Subjects Effects

Dependent Variable:Mean % Retention

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	94237.876[a]	11	8567.080	22.915	.00000
Intercept	636944.138	1	636944.138	1703.684	.00000
SoilDepth	2332.198	1	2332.198	6.238	.01351
RoofSlope	2469.156	1	2469.156	6.604	.01108
RainCategory	88787.748	2	44393.874	118.744	.00000
SoilDepth* RoofSlope	433.041	1	433.041	1.158	.28344
SoilDepth* RainCategory	51.533	2	25.766	.069	.93343
RoofSlope * RainCategory	177.748	2	88.874	.238	.78870
SoilDepth* RoofSlope * RainCategory	31.929	2	15.964	.043	.95821
Error	59818.052	160	373.863		
Total	804114.710	172			
Corrected Total	154055.928	171			

a. R Squared = .612 (Adjusted R Squared = .585)

B.2.2 Small Rain Events

Between-Subjects Factors[a]

		N
MediaDepth	4"	30
	6"	30
RoofSlope	2%	30
	33.3%	30
RainCategory	1	60

a. RainCategory = 1

Tests of Between-Subjects Effects[b]

Dependent Variable:Mean % Retention

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1170.831[a]	3	390.277	.751	.52622
Intercept	446895.921	1	446895.921	860.268	.00000
MediaDepth	683.168	1	683.168	1.315	.25635
RoofSlope	369.222	1	369.222	.711	.40278
RainCategory	.000	0	.	.	.
MediaDepth * RoofSlope	118.442	1	118.442	.228	.63487
MediaDepth * RainCategory	.000	0	.	.	.
RoofSlope * RainCategory	.000	0	.	.	.
MediaDepth * RoofSlope * RainCategory	.000	0	.	.	.
Error	29091.119	56	519.484		
Total	477157.871	60			
Corrected Total	30261.951	59			

a. R Squared = .039 (Adjusted R Squared = -.013)

b. RainCategory = 1

B.2.3 Medium Rain Events

Between-Subjects Factors[a]

		N
MediaDepth	4"	28
	6"	28
RoofSlope	2%	28
	33.3%	28
RainCategory	2	56

a. RainCategory = 2

Between-Subjects Factors[a]

		N
MediaDepth	4"	28
	6"	28
RoofSlope	2%	28
	33.3%	28
RainCategory	2	56

Dependent Variable:Mean % Retention

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1533.489[a]	3	511.163	1.239	.30492
Intercept	237174.949	1	237174.949	575.005	.00000
SoilDepth	580.244	1	580.244	1.407	.24099
RoofSlope	876.586	1	876.586	2.125	.15091
RainCategory	.000	0	.	.	.
SoilDepth * RoofSlope	76.658	1	76.658	.186	.66818
SoilDepth * RainCategory	.000	0	.	.	.
RoofSlope * RainCategory	.000	0	.	.	.
SoilDepth * RoofSlope * RainCategory	.000	0	.	.	.
Error	21448.685	52	412.475		
Total	260157.123	56			
Corrected Total	22982.174	55			

a. R Squared = .067 (Adjusted R Squared = .013)

b. RainCategory = 2

B.2.4 Large Rain Events

Between-Subjects Factors[a]

		N
MediaDepth	4"	28
	6"	28
RoofSlope	2%	28
	33.3%	28
RainCategory	3	56

a. RainCategory = 3

Tests of Between-Subjects Effects[b]

Dependent Variable:Mean % Retention

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2745.807[a]	3	915.269	5.130	.00349
Intercept	54775.661	1	54775.661	306.991	.00000
SoilDepth	1113.662	1	1113.662	6.242	.01568
RoofSlope	1364.133	1	1364.133	7.645	.00786
RainCategory	.000	0	.	.	.
SoilDepth * RoofSlope	268.013	1	268.013	1.502	.22587
SoilDepth * RainCategory	.000	0	.	.	.
RoofSlope * RainCategory	.000	0	.	.	.
SoilDepth * RoofSlope * RainCategory	.000	0	.	.	.
Error	9278.248	52	178.428		
Total	66799.716	56			
Corrected Total	12024.055	55			

a. R Squared = .228 (Adjusted R Squared = .184)

b. RainCategory = 3

B.3 ANOVA Model and Tukey HSD: Roof Treatment and Rain Category

B.3.1 All RainEvents

Between-Subjects Factors

		N
Roof Treatment	F4	43
	F6	43
	S4	43
	S6	43
RainCategory	1	60
	2	56
	3	56

Tests of Between-Subjects Effects

Dependent Variable:Mean % Retention

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	94237.876[a]	11	8567.080	22.915	.00000
Intercept	636944.138	1	636944.138	1703.684	.00000
Treatment	5234.395	3	1744.798	4.667	.00373
RainCategory	88787.748	2	44393.874	118.744	.00000
Treatment * RainCategory	261.209	6	43.535	.116	.99436
Error	59818.052	160	373.863		
Total	804114.710	172			
Corrected Total	154055.928	171			

a. R Squared = .612 (Adjusted R Squared = .585)

Multiple Comparisons

Mean % Retention

TukeyHSD

(I) Roof Treatment	(J) Roof Treatment	Mean Difference (I-J)	Std. Error	Sig.	97.5% Confidence Interval	
					Lower Bound	Upper Bound
F4	F6	-10.5207	6.41986	.35977	-28.8289	7.7875
	S4	4.3542	6.41986	.90523	-13.9540	22.6624
	S6	.1667	6.41986	.99999	-18.1415	18.4750
F6	F4	10.5207	6.41986	.35977	-7.7875	28.8289
	S4	14.8749	6.41986	.09824	-3.4334	33.1831
	S6	10.6874	6.41986	.34563	-7.6208	28.9957
S4	F4	-4.3542	6.41986	.90523	-22.6624	13.9540
	F6	-14.8749	6.41986	.09824	-33.1831	3.4334
	S6	-4.1874	6.41986	.91463	-22.4957	14.1208
S6	F4	-.1667	6.41986	.99999	-18.4750	18.1415
	F6	-10.6874	6.41986	.34563	-28.9957	7.6208
	S4	4.1874	6.41986	.91463	-14.1208	22.4957

Based on observed means.

The error term is Mean Square(Error) = 886.113.

Mean % Retention

TukeyHSD[a,,b]

Roof Treatment	N	Subset	
		1	2
S4	43	55.6228	
S6	43	59.8102	59.8102
F4	43	59.9770	59.9770
F6	43		70.4977
Sig.		.724	.054

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square(Error) = 373.863.

a. Uses Harmonic Mean Sample Size = 43.000.

b. Alpha = .025.

B.3.2 Small Rain Events

Between-Subjects Factors[a]

		N
Roof Treatment	F4	15
	F6	15
	S4	15
	S6	15
RainCategory	1	60

a. RainCategory = 1

Tests of Between-Subjects Effects[b]

Dependent Variable:Mean % Retention

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1170.831[a]	3	390.277	.751	.52622
Intercept	446895.921	1	446895.921	860.268	.00000
Treatment	1170.831	3	390.277	.751	.52622
RainCategory	.000	0	.	.	.
Treatment * RainCategory	.000	0	.	.	.
Error	29091.119	56	519.484		
Total	477157.871	60			
Corrected Total	30261.951	59			

a. R Squared = .039 (Adjusted R Squared = -.013)

b. RainCategory = 1

Multiple Comparisons[a]

Mean % Retention

TukeyHSD

(I) Roof Treatment	(J) Roof Treatment	Mean Difference (I-J)	Std. Error	Sig.	97.5% Confidence Interval	
					Lower Bound	Upper Bound
F4	F6	-9.5587	8.32253	.66134	-33.8867	14.7694
	S4	2.1513	8.32253	.99388	-22.1767	26.4794
	S6	-1.7873	8.32253	.99646	-26.1154	22.5407
F6	F4	9.5587	8.32253	.66134	-14.7694	33.8867
	S4	11.7100	8.32253	.50036	-12.6181	36.0381
	S6	7.7713	8.32253	.78688	-16.5567	32.0994
S4	F4	-2.1513	8.32253	.99388	-26.4794	22.1767
	F6	-11.7100	8.32253	.50036	-36.0381	12.6181
	S6	-3.9387	8.32253	.96465	-28.2667	20.3894
S6	F4	1.7873	8.32253	.99646	-22.5407	26.1154
	F6	-7.7713	8.32253	.78688	-32.0994	16.5567
	S4	3.9387	8.32253	.96465	-20.3894	28.2667

Based on observed means.

The error term is Mean Square(Error) = 519.484.

a. RainCategory = 1

B.3.3 Medium Rain Events

Between-Subjects Factors[a]

		N
Roof Treatment	F4	14
	F6	14
	S4	14
	S6	14
RainCategory	2	56

a. RainCategory = 2

Tests of Between-Subjects Effects[b]

Dependent Variable:Mean % Retention

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1533.489[a]	3	511.163	1.239	.30492
Intercept	237174.949	1	237174.949	575.005	.00000
Treatment	1533.489	3	511.163	1.239	.30492
RainCategory	.000	0	.	.	.
Treatment * RainCategory	.000	0	.	.	.
Error	21448.685	52	412.475		
Total	260157.123	56			
Corrected Total	22982.174	55			

a. R Squared = .067 (Adjusted R Squared = .013)

b. RainCategory = 2

Multiple Comparisons[a]

Mean % Retention

TukeyHSD

(I) Roof Treatment	(J) Roof Treatment	Mean Difference (I-J)	Std. Error	Sig.	97.5% Confidence Interval	
					Lower Bound	Upper Bound
F4	F6	-8.7779	7.67626	.66458	-31.2813	13.7256
	S4	5.5729	7.67626	.88626	-16.9306	28.0763
	S6	1.4750	7.67626	.99745	-21.0284	23.9784
F6	F4	8.7779	7.67626	.66458	-13.7256	31.2813
	S4	14.3507	7.67626	.25365	-8.1527	36.8541
	S6	10.2529	7.67626	.54485	-12.2506	32.7563
S4	F4	-5.5729	7.67626	.88626	-28.0763	16.9306
	F6	-14.3507	7.67626	.25365	-36.8541	8.1527
	S6	-4.0979	7.67626	.95042	-26.6013	18.4056
S6	F4	-1.4750	7.67626	.99745	-23.9784	21.0284
	F6	-10.2529	7.67626	.54485	-32.7563	12.2506
	S4	4.0979	7.67626	.95042	-18.4056	26.6013

Based on observed means.

The error term is Mean Square(Error) = 412.475.

a. RainCategory = 2

Mean % Retention [c]

TukeyHSD[a,,b]

Roof Treatment	N	Subset
		1
S4	14	59.0736
S6	14	63.1714
F4	14	64.6464
F6	14	73.4243
Sig.		.254

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square(Error) = 412.475.

a. Uses Harmonic Mean Sample Size = 14.000.

b. Alpha = .025.

c. RainCategory = 2

B.3.4 Large Rain Events

Between-Subjects Factors[a]

		N
Roof Treatment	F4	14
	F6	14
	S4	14
	S6	14
RainCategory	3	56

a. RainCategory = 3

Tests of Between-Subjects Effects[b]

Dependent Variable:Mean % Retention

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2745.807[a]	3	915.269	5.130	.00349
Intercept	54775.661	1	54775.661	306.991	.00000
Treatment	2745.807	3	915.269	5.130	.00349
RainCategory	.000	0	.	.	.
Treatment * RainCategory	.000	0	.	.	.
Error	9278.248	52	178.428		
Total	66799.716	56			
Corrected Total	12024.055	55			

a. R Squared = .228 (Adjusted R Squared = .184)

b. RainCategory = 3

Multiple Comparisons[a]

Mean % Retention

TukeyHSD

(I) Roof Treatment	(J) Roof Treatment	Mean Difference (I-J)	Std. Error	Sig.	97.5% Confidence Interval	
					Lower Bound	Upper Bound
F4	F6	-13.2943	5.04873	.05256	-28.0950	1.5064
	S4	5.4957	5.04873	.69803	-9.3050	20.2964
	S6	.9521	5.04873	.99759	-13.8485	15.7528
F6	F4	13.2943	5.04873	.05256	-1.5064	28.0950
	S4	18.7900*	5.04873	.00267	3.9893	33.5907
	S6	14.2464	5.04873	.03310	-.5542	29.0471
S4	F4	-5.4957	5.04873	.69803	-20.2964	9.3050
	F6	-18.7900*	5.04873	.00267	-33.5907	-3.9893
	S6	-4.5436	5.04873	.80488	-19.3442	10.2571
S6	F4	-.9521	5.04873	.99759	-15.7528	13.8485
	F6	-14.2464	5.04873	.03310	-29.0471	.5542
	S4	4.5436	5.04873	.80488	-10.2571	19.3442

Based on observed means.

The error term is Mean Square(Error) = 178.428.

*. The mean difference is significant at the .025 level.

a. RainCategory = 3

Mean % Retention [c]

TukeyHSD[a,,b]

Roof Treatment	N	Subset	
		1	2
S4	14	24.0679	
S6	14	28.6114	28.6114
F4	14	29.5636	29.5636
F6	14		42.8579
Sig.		.698	.033

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square(Error) = 178.428.

a. Uses Harmonic Mean Sample Size = 14.000.

b. Alpha = .025.

c. RainCategory = 3