VEGETATED ROOFS FOR URBAN ECOSYSTEM REMEDIATION: PERFORMANCE AND POLICY IN THE TANYARD BRANCH WATERSHED

by

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(Under the Direction of Laurie Fowler)

ABSTRACT

Urban land area in the United States is projected to increase to 8.1% of total land area by the year 2050. These human-dominated environments create conditions that degrade both terrestrial and aquatic ecosystems. If cities are to reduce their environmental impact, innovative practices must be developed that replace ecosystem services lost during the urbanization process. This study evaluated the performance and feasibility of using vegetated or green roof systems for urban ecosystem remediation. The stormwater retention performance of a thin-layer green roof was evaluated using an experimental field test plot. Average stormwater retention was found to be slightly under 78% of rainfall from storm events over the course of one year. The additional stormwater storage created on the rooftop allowed for a curve number of 86 to be developed for the green roof. This curve number was then used in a modeling analysis of Tanyard Branch watershed, a highly urbanized watershed in Athens, Georgia. Spatial analysis demonstrated how impervious surface cover could be reduced in the watershed by using green roofs. Total impervious area in the downtown commercial zone was reduced 20% when all the roofs were greened. Roof greening also resulted in significant hydrologic changes in the watershed as both peak watershed storm flows and total storm flow volumes were reduced, most notably for small storm events. A benefit-cost analysis (BCA) was also performed for the life cycle of the green roof system. In Tanyard Branch, the net present values of green roofs are greater than traditional roofing although expected changes in technology, energy prices, and market conditions were shown to reduce green roof life cycle costs to below traditional roofing costs. A green roof policy was developed for Athens, GA based on the performance and economic analysis of the experimental green roof. This policy uses private incentives and public demonstration sites to promote green roof infrastructure. A stormwater best management practice specification for green roofs was created that may be included in future versions of the Georgia Stormwater Management manual. Green roofs are shown to be a potentially valuable tool for increased sustainability in highly developed urban areas.

INDEX WORDS: urban ecology, environmental policy, green roof, hydrology, stormwater

VEGETATED ROOFS FOR STORMWATER MANAGEMENT: PERFORMANCE AND POLICY IN THE TANYARD BRANCH WATERSHED

by

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B.S. University of Tennessee Knoxville, 2000

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2006

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August 2006

DEDICATION

To Katy, who never thought she would marry the green roof guy

ACKNOWLEDGEMENTS

Financial support for this study provided by the Georgia Forestry Commission's Urban and Community Forestry grant program, University of Georgia's Dissertation Completion Fellowship, University of Georgia River Basin Center, Georgia Air and Waste Management Association, Georgia Association of Water Professionals, and National Wildlife Federation's Campus Ecology Fellowship.

Material support was provided by the Home Depot, Saul Nurseries, ItSaul Natural, American Hydrotech.

I thank Dr. Todd Rasmussen and Chris Holliday for invaluable technical assistance and support in the construction of the green roof experimental plot. I acknowledge David Gattie, Rhett Jackson, Andy Keeler and Judy Meyer for their comments and feedback on this work. I additionally thank Roger Hilten and Eric Prowell for their interest in the project, and the volunteers who helped in construction.

Finally, I thank Laurie Fowler for her constant support and generous commitment of her time and resources in this work. Her investment in me personally and dedication to this project made my graduate work a positive experience.

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CHAPTER 1

INTRODUCTION

Background

Although ecology is a relatively recent field of study when compared with other natural sciences, it has been in existence long enough to have developed distinct specialties. Whether dividing the discipline by scale (landscape ecology, ecosystem ecology, population ecology and community ecology), organism (animal ecology, plant ecology, insect ecology) or through synergy with other disciplines (chemical ecology, statistical ecology, genetic ecology), ecological science has truly embraced an interdisciplinary approach to studying interactions between living and nonliving components of the planet.

In the recent decades a new subfield of ecology, urban ecology has been developed. The phrase urban ecology was originally used by sociologists to describe human behavior in urban areas (Collins et al, 2000). Ecologists have borrowed the term in their study of the interactions between biotic and abiotic elements in human dominated ecosystems. This area of ecology has focused both on the "ecology in cities" and the "ecology of cities" (Grimm et al, 2000).

Studies of ecology in cities are numerous (see Rebele, 1994; Sadler et al, 2006; Fanelli et al, 2006). They are often performed over a gradient of sites from "pristine" environments to human-dominated areas (McDonnell and Pickett, 1990; McKinney, 2002). Indicator variables such as impervious surface cover (Sonneman et al, 2001), percent urban land cover (Morley and Karr, 2002), and drainage connection (Walsh, 2004) are correlated with measures of ecological health to demonstrate the impacts of human dominated environments on their "natural" counterparts. Traditional ecological metrics like distribution and abundance of indicator species, nutrient uptake lengths, and composite biological metrics are used to identify the effect that cities are having on the area (Paul and Meyer, 2001; Parris, 2006). This type of research treats cities and towns as external to the "natural" environment and the ecological processes that occur in landscapes not occupied by humans.

When studying the ecology of cities, researchers view the city or urban area as a unique ecosystem with measurable energy flows, distinct urban biogeochemistry (Kaye et al, 2006), and completely restructured flora and fauna assemblages driven by human behavior (Shochat et al, 2006). Wackernagel and Rees (1996) developed the idea of an ecological footprint which is, simply stated, the amount of land and sea necessary to sustain human populations in a given area. This approach attempts to budget the metabolism of a city into quantified energy and matter flows so that sustainable practices can be identified and realized (Rees, 2000).

Additionally, the inclusion of human decision-making into urban ecological studies has spawned a number of conceptual models attempting to capture the complexity of interactions that occur in the urban landscape. The Human Ecosystem Model proposed by Machlis et al (1997) identifies both natural and social resources as well as human institutions required for modeling ecological processes in the human-dominated environment. This concept is expanded to include spatial components (Pickett et al, 1997) and has proved essential in long term urban ecological studies (Pickett and Cadenasso, 2006). Other conceptual models have provided a framework where human and biophysical drivers produce changes in human and biophysical patterns and processes (Alberti et al, 2003). Alberti et al (2003) gives an example of this model where population growth (driver) results in increased impervious cover (patterns) leading to increased stormwater runoff and erosion (processes) degrading water quality and aquatic habitat (effects) which may result in a new land use policy (driver).

A natural outflow of the ecology of city paradigm is the idea that the city can be developed in such a way as to restore and retain ecosystem services and, in some cases, create them. This can be accomplished through a variety of avenues. The development of urban greenspace plans and green corridors directly preserve patches of habitat and environmentally sensitive areas in the urban fabric which may be important for recolonization potential as well as maintenance of existing biotic community structure (Snep et al, 2006). Ecosystem services such as water regulation and supply, erosion control and sediment retention, nutrient cycling, and climate regulation all are greatly affected by the development process. These impacts can be minimized and services restored through landscape design, green space preservation, and engineered solutions.

Opportunities for environmental remediation abound specifically in the built environment. Converting roads and parking lots from sealed surfaces to porous pavement allows for the transportation system to lessen its impact on receiving water bodies (Ferguson, 2005). Buildings can also be designed and built in a way that minimizes the negative environmental impact traditionally inflicted by conventional construction practices. Sustainable water use for a building may involve xeriscaping, grey water reuse for irrigation, and the use of low-flow or composting toilets and non-water urinals (Gleick, 2003).

One specific component of the built environment often overlooked is the use of the rooftop as environmentally beneficial space. Rooftops comprise a large proportion of surface land area particularly in downtown regions of the city as building footprints can occupy entire city blocks. Transforming the rooftop space into an environmental amenity can add value to the building owner and perform ecosystem services in the city. This transformation can be accomplished by applying vegetation and engineering growing media to the roof surface and creating a "green" roof. The rooftop is then able to retain and utilize stormwater for plant growth, reduce building temperatures through shading by the plants and evaporative cooling, and increase urban habitat. The practice of designing and building green roofs is becoming increasingly popular with architects, landscape architects, stormwater managers and ecological design firms in densely developed urban areas.

There are two general types of modern green roof systems: intensive and extensive. Intensive systems are characterized by deep (> 6") growing media, opportunities for a diverse plant palate on the rooftop and high cost and maintenance requirements. Extensive systems are designed to be lightweight and easily retrofitted on existing roof surfaces. They contain thin growing media depths (2-6") and can support a limited number of drought-tolerant plants that thrive in the limited water and nutrient conditions. Extensive systems are by far the most common in Germany with over 80% of green roofs being extensive in 2002 (Harzmann, 2002)

Green roof literature review

While green roofs can be traced to ancient times (Dunnett and Kingsbury, 2004), current green roofs do not bear significant resemblance to their forbearers as they use highly specialized synthetic materials and engineered growing media. Modern green roof studies were first performed in Germany in the early 1960's by Reinhard Bornkamm who evaluated vegetation establishment on gravel roofs (Bornkamm, 1961). Bornkamm is considered the father of modern green roofs and his early study sites are still intact in Berlin (Earth Pledge, 2005). Other early German researchers include H.L. Liesecke who founded the Landscaping and Landscape Development Research Society (FLL) and performed a number of early studies at the University of Hannover. Liesecke established testing protocols for German green roof systems and his extensive research into green roof rainfall runoff relationships has been published in German journals (Liesecke, 1998; Liesecke, 1999).

Outside of Germany, relatively little peer-reviewed research exists on green roof systems. A number of books have been published recently providing general guidance and examples for green roof installers. Osmundson (1999) published a general overview of roof gardens covering a variety of installation techniques and numerous examples. Two other green roof books have been released since then with Dunnett and Kingbury (2004) and Earth Pledge (2005) both containing valuable case studies and examples of green roof installations.

Scientific green roof literature includes horticultural establishment methods, quantification of environmental benefits such as stormwater management, thermal conductance and biodiversity on the roof, economic evaluations and policy analyses. Rooftops present a unique challenge for plants as they have extreme temperatures and very limited nutrients and water. Boivin et al (2001) describe the effect of freezing temperatures on six herbaceous perennials and recommended using 4” of growing media substrate for green roofs in northern latitudes. The use of plants from the genus *Sedum* are the most common and studies have shown that these plants can remain viable even after 88 days of drought (VanWoert et al, 2005). Native plant taxa may survive but often need supplemental irrigation while *Sedum* can thrive without the additional water (Monterusso et al, 2005).

Stormwater research has focused on quantifying the stormwater retention properties of green roof systems. Using simulated green roof platforms in Michigan, VanWoert et al (2005) evaluated the rainfall retention of extensive green roof systems with a variety of substrate depths, roof slopes and cover types and found both slope and growing media depth to be important factors in green roof stormwater retention. They found a roof with 2.5 cm of growing media and 1.5 cm of moisture retention fabric retained over 60% of the year's cumulative rainfall with over 95% of the rainfall from small storm events (<2 mm) being retained (2005). Other studies have also found that green roof stormwater retention diminishes as slope increases (Villarreal and Bengtsson, 2005). Retention results vary depending on the specifications of the green roof with results ranging from nearly 40% to over 60% of annual rainfall retained (Bengtsson et al, 2005; DeNardo et al, 2003; Moran, 2004).

The ability of green roofs to mitigate roof temperatures and decrease the heating and cooling load of buildings is another area of active research. Studies use experimental test plots combined with modeling methodology to demonstrate the cooling effects of vegetated roof cover primarily through evapotranspiration (Onmura, 2001; Lazzarin et al, 2005; Hilten, 2005). The shading effect from vegetation also is shown to have an effect in lessening roof temperatures (Del Barrio, 1998). European studies are based in the Mediterranean areas where climatic conditions allow for significant evaporation and passive cooling to occur (Theodosiou, 2003; Eumorfopoulou and Aravantinos, 2003).

Reduction in roof temperature also translates into reduced heat fluxes in and out of a building. In general, roof greening tends to lessen the peak temperatures of the roof, both high and low, potentially lowering the heating and cooling loads for the building. Researchers have shown green roofs reduce these temperature peaks by functioning as an additional insulation layer (Del Barrio, 1998) as well as increasing the solar reflectivity (albedo) of the rooftop (Akbari, 2003; Gaffin et al, 2005). Whether this reduction in heat flux translates into significant energy savings is not clear from the literature. In one study, energy use was evaluated for small experimental sheds containing green roofs and the vegetated treatments had little effect on total energy use in each structure (DeNardo et al, 2003). Other research, however, suggests that considerable energy cost savings can be realized when green roofs are used. A green roof in India was modeled to save the building 3.02 kWh per day (Kumar and Kaushik, 2005) and a study in Singapore demonstrated enough energy savings effect for the life cycle cost of a green roof to be less than a traditional roof when energy savings were included in the analysis (Wong et al 2003b).

The green roof's ability to add habitat and biodiversity in urban areas is an important, but understudied aspect of the practice (Brenneisen, 2005). From a landscape scale, green roofs can connect patches of remnant urban green space and provide urban habitat networks in densely developed areas (Kim, 2004). At the roof scale, Brenneisen (2003) found spontaneously colonized green roofs to contain 78 spider and 254 beetle species after three years of growth with 18% of spider species and 11% of beetle species classified as rare or endangered. Green roofs in London have been shown to preserve habitat for the black redstart, a rare bird species targeted for conservation (Gedge, 2003). A number of biotic surveys have shown green roofs to increase the presence of macroinvertebrate assemblages and avian fauna (Gedge and Kadas, 2004; Coffman and Davis, 2005).

Finally, a number of studies have quantified the economic costs and benefits of installing green roof systems. Peck et al (1999) were among the first to detail the costs and benefits associated with all types of green roof systems. Their work was primarily a qualitative description of all the potential benefits ranging from stormwater management and temperature regulation to horticultural therapy and aesthetic improvements (1999). While this is effective for advocacy purposes, it can be misleading to try to apply all the benefits described in the study to extensive systems, the most common green roof application. One study in Singapore demonstrated that energy savings alone make extensive systems more cost-effective than traditional roofing (Wong et al, 2003b).

Outline of current study

The objectives of this study were 1) to evaluate the stormwater retention performance of an extensive green roof system, 2) to examine the watershed scale effects of widespread extensive green roof implementation, 3) perform a cost-benefit analysis of extensive green roof systems, and 4) evaluate policy tools that may encourage green roof implementation. The interdisciplinary nature of this study reflects the recognition that urban environments must be studied holistically to include human decision-making as an essential biotic component in the structure of the urban ecosystem for remediation to be successful.

The dissertation follows a manuscript style with four chapters that either have been or will be submitted to peer-reviewed journals. Chapter two focuses on the stormwater retention performance of an experimental green roof test plot established in Athens, GA. A paired green roof - black roof test plot was constructed at the University of Georgia and monitored between November 2003 and November 2004 for its effectiveness in reducing stormwater flows. Stormwater mitigation performance was monitored for 31 precipitation events. Green roof precipitation retention, stormwater runoff times, and the development of a hydrologic modeling parameter are discussed.

Chapter three uses the hydrologic data collected from the green roof and detailed spatial analysis to model the effect that widespread roof greening would have across Tanyard Branch watershed. The change in hydrology was investigated at four spatial scales to account for land use diversity within the watershed. Stormwater outflow of the receiving water body was modeled under hypothetical roof greening scenarios to determine their effect on the flow regime of an urban stream system. These results were also evaluated in light of existing state water management standards.

Chapter four is an economic benefit cost analysis (BCA) of green roof systems. Using data collected from local green roof plots, a BCA is performed for the life cycle of thin-layer green roof systems in an urban watershed. The net present value (NPV) of extensive green roof systems are compared with traditional roofing practices for both private and public interests. Sensitivity analysis performed on the cost data allows for realistic projections for the establishment of widespread green roof implementation.

Chapter five evaluates existing green roof policy and develops green roof policy recommendations for Athens, GA. The authors first describe the federal framework for green roof policies in countries with established green roof programs. Existing local policies that have been developed internationally and more recently in select major North American cities are then evaluated. These policies fall into a number of distinct categories and the advantages, disadvantages and key features of each category are discussed. Finally, a model policy is developed for the jurisdiction of Athens, Georgia to demonstrate the importance of customizing green roof policy to local conditions. Included in this analysis is the creation of a stormwater best management practice specification for green roof systems.

CHAPTER 2

HYDROLOGIC BEHAVIOR OF VEGETATED ROOFS[1]

[1] Carter, T.L. and Rasmussen, T.C. Accepted by *Journal of American Water Resources Association.* Reprinted here with permission of publisher, 05/25/06

Abstract

Control of stormwater runoff from impervious surfaces is an important national goal because of disruptions to downstream ecosystems, water users, and property owners caused by increased flows and degraded quality. One method for reducing stormwater is the use of vegetated (green) roofs, which efficiently detain and retain stormwater when compared to conventional (black) roofs. A paired green roof - black roof test plot was constructed at the University of Georgia and monitored between November 2003 and November 2004 for its effectiveness in reducing stormwater flows. Stormwater mitigation performance was monitored for 31 precipitation events, which ranged in depth from 0.28 to 8.43 cm. Green roof precipitation retention decreased with precipitation depth; ranging from just under 90% for small storms (< 2.54 cm) to slight less than 50%for larger storms (> 7.62 cm). Runoff from the green roof was also delayed - average runoff lag times increased from 17.0 minutes for the black roof to 34.9 minutes for the green roof, an average increase of 17.9 minutes. Precipitation and runoff data were also used to estimate the green roof curve number, CN = 86. This information can be used in hydrologic models for developing stormwater mitigation programs.

INDEX WORDS: environmental impacts, urbanization, best management practices, storm water management, impervious surfaces, vegetated roofs

Introduction

The built environment is often implicated as a causal agent in degradation of stream ecosystems near urban centers (Booth and Jackson, 1997; Finkenbine et al., 2000; Wang et al., 2001). Impervious surface cover (ISC) adversely affects stream ecosystems due to the reduction of soil infiltration (Arnold and Gibbons, 1996) and the concomitant increase in the rate and volume of stormwater inflow to receiving water bodies (Brabec et al., 2002). Anthropogenic pollutants are also transported in this runoff - both in suspended and sediment-bound forms - leading to poor water quality and unhealthy streams (Karr, 1999; Randhir, 2003). The increase in stormwater volume also affects the physical characteristics of urban streams (Bhaduri et al., 2000).

In the past, stormwater management focused on conveyances to route stormwater runoff from urban centers into nearby rivers, streams, and lakes. Dramatic engineering solutions - often for flood control - include armoring stream banks with concrete or riprap, straightening channels, and stream piping (Dunne and Leopold, 1978). Yet, increased stormwater flows can be amplified by kinematic processes as they travel through the municipality's storm sewer system. The resulting biotic community is frequently dominated by a few tolerant species of fish and macroinvertebrates which can withstand harsh hydrologic conditions and impaired water quality (Miltner et al., 2004).

These detrimental effects of urbanization and altered hydrology on the chemical, physical, and biological properties of stream ecosystems have resulted in regulations at the federal, state and local levels requiring government agencies to develop management strategies to mitigate the adverse environmental impacts of development. The Clean Water Act established the National Pollutant Discharge Elimination System permitting process which authorizes the federal or state government to implement stormwater discharge permitting system (Ferrey, 2004). Stormwater permits are designed to reduce adverse stormwater impacts on receiving water bodies.

Under Georgia Environmental Protection Division's Municipal Separate Storm Sewer System (MS4) permit program, local governments are required to develop a stormwater management program which includes structural and nonstructural stormwater controls. Non-structural controls are primarily encompassed in better site design practices. Structural controls are “constructed stormwater management facilities designed to treat stormwater runoff and/or mitigate the effects of increased stormwater runoff peak rate, volume, and velocity due to urbanization” (ARC, 2001).

One component of the MS4 program is the requirement to use stormwater Best Management Practices (BMPs). Common BMPs include stormwater ponds and wetlands, bioretention areas, porous pavements, vegetated swales, and vegetated filter strips. These approaches can be used to meet a variety of design goals including water quality enhancement, channel protection, overbank flood protection, and extreme flood protection. While these stormwater BMPs are useful in urbanizing areas where land is readily available, undeveloped land in many metropolitan areas is scarce and stormwater management must be retrofitted into the built environment.

Remarkably, roofs have been overlooked in the United States as management tools for stormwater and urban environmental problems. This is in spite of the fact that roofs may constitute a substantial fraction of the total ISC, particularly in highly urbanized watersheds where the ISC > 50%. Vegetated roof cover, also called green roofs, provide a way for roofs to be used beneficially in an urban environment, rather than contributing to stormwater problems.

Green roofs use engineered growing media, drought-tolerant plants, and specialized roofing materials installed on existing structures (Peck et al., 1999). This creates a rooftop which can absorb and retain the stormwater that falls upon the rooftop rather than quickly shedding the water into stormwater conveyance systems.

Green roofs (e.g., thatched, sod) have traditionally been used in Europe, but only recently has their use become popular in North America for environmental purposes, such as green space and water quality remediation. Little published research exists in North America on the stormwater retention performance of green roof systems with the majority of studies reported at annual conferences (GRHC, 2003; GRHC, 2004) or anecdotal reports found in popular literature (Taylor, 2003; Dunnett, 2004). Notable exceptions include recent studies by VanWoert et al. (2005) and Monterusso et al. (2004) which reported stormwater retention performance for small test plots in central Michigan. Research in English-language journals is weighted towards green roof energy budget studies (Del Barrio and E. Palomo, 1998; Niachou et al., 2001; Wong et al., 2003a) or horticultural aspects of vegetated roof systems (Emilsson and Rolf, 2005; Monterusso et al., 2005) rather than stormwater retention. Germany has been a leader in testing and institutionalizing green roof technology with guidelines for planning, execution, and upkeep of green roof construction (FLL, 1995). German research is published in German and few translated reports are available.

Stormwater BMPs are often classified as infiltration, detention, or retention systems (EPA, 1999). These systems are all designed to retain stormwater before eventually releasing it into the stream system either through groundwater recharge or directly from an outlet pipe. Structural BMPs such as stormwater detention ponds change hydrology through peak shaving which reduces the peak flow rate, but increases the duration of the flows having the greatest affect on channel geomorphology (Bledsoe, 2002; MacRae, 1997).

The primary goal of this study was to design, install, and evaluate a vegetated roof test plot to evaluate its potential for use as a stormwater BMP in highly developed urban watersheds. The vegetated plot was designed to be lightweight, easily replicated, and cost-efficient. A second goal of this study was to develop protocol for testing and monitoring of the stormwater retention performance of green roofs, particularly for large retrofit projects. The need for scientific data on stormwater BMP performance is pressing in light of recent regulations (EPA, 2002). The expectation is that stormwater retention data presented here will provide stormwater professionals and researchers a basis for incorporating green roofs into development scenarios and watershed management plans.

Methods and Materials

Study Site Description

The study site is located on the ground-floor roof of the Boyd Graduate Studies Building (33.943° N, 87.375° W), located on the University of Georgia (UGA) campus in Athens, Georgia. Athens is located in northeast Georgia, approximately 100 km east of Atlanta. This region of Georgia averages approximately 123.2 cm of rainfall per year with March typically having the highest total rainfall. The observed precipitation during the study period (November 2003 to November 2004) was slightly less than average at 107.9 cm (Figure 2.1). While most months were drier than normal, two months were substantially wetter (November 2003 and September 2004) than normal. The remnants of four hurricanes were the cause of the extreme rainfall during September 2004.

Two test plots were placed on an existing flat (< 2% slope) roof section. The roof was selected for its accessibility, ability to accommodate additional weight, and high visibility for public education. The roof section is at ground level next to the UGA Science Library. The test area is surrounded by two six-story towers on the east and west sides which limit direct sunlight to approximately six hours per day in the summer and nine hours per day in the winter. The roof contains an internal drainage system which is directly connected to the campus stormwater collection and conveyance system.

The test plots were isolated from the rest of the roof using pressure-treated lumber and additional waterproofing materials. The size of the test plots was constrained by the existing rooftop drainage system, with each section directing rainfall to a single, internal roof drain. The test and control sites are identical in size and shape at 5.2 m x 8.2 m for a total of 42.64 m^2 (Figure 2.2). The control plot (black roof) was left in its original state. The control plot - similar to many urban rooftops in its slope and construction - included a concrete deck overlaid with approximately 25 cm of perlite insulation, a waterproofing membrane consisting of alternating layers of liquid-applied asphalt and fiberglass-reinforced asphalt-saturated felt, and approximately 5 cm of gravel ballast.

The experimental plot (green roof) was retrofitted with a vegetated soil system (Figure 2.3). The original gravel within the plot was removed and the section was visually inspected to identify potential problem areas in the waterproofing layer which were then patched. The vegetated section uses a design from American Hydrotech, Inc., primarily comprised of loose-laid synthetic specialized layers underneath the growing media and plant material. The specialized layers include: a WSF40 root protection sheet of negligible thickness, a SSM 45 moisture retention mat approximately .48 cm thick, a Floradrain FD40 synthetic drainage panel approximately 3.81 cm thick, and a Systemfilter SF geotextile filter sheet of negligible thickness. The water retention capacity of the moisture retention mat is approximately 5 l/m^2 and the water retention capacity of the synthetic drainage panel is approximately 4 l/m^2 (American Hydrotech Inc., 2002). The growing media is a Lightweight Roof Garden mix provided by ItSaul Natural, LLC. This soil mix is a blend of 55% Stalite expanded slate, 30% United States Golf Association sand, and 15% composted organic matter composed primarily of worm castings. This media has a bulk density of 1.508 g/cm^3 and the total porosity is 50.6%. The soil mix was spread to a depth of 7.62 cm across the plot.

Six drought-tolerant plant species were selected for their ability to survive low nutrient conditions and extreme temperature fluctuations found at the roof surface. The species included *Sedum album* “Murale”, *Sedum album* “Jellybean”, *Sedum kamtschaticum*, *Sedum sexangulare*, *Delosperma nubigenum*, and *Delosperma cooperi*. The plants were supplied as 3.4 x 3.4 x 6.25 cm plugs which were planted in the growing media at a density of 50 $plants/m^2$.

Discharge Measurement

The original drains beneath the control and test plot sections were disconnected and rerouted through two 120-cm × 30-cm × 30-cm stainless-steel weirs. These weirs were located in the building basement directly below the experimental plots (Figure 2.4). There was negligible travel time from the surface drain to the weirs through the drainage pipe. The weir was designed using a two-stage riser setup. The primary weir outlet was a 2.54-cm circular open orifice located 15.24 cm from the bottom of the weir box. A second, rectangular weir outlet was placed at the top of each weir box to accommodate runoff during extreme events. No storm event produced enough runoff to overflow into the second outlet. Weir outflow was routed to the original stormwater collection and conveyance system for the building.

Druck PDCR 1800 pressure transducers were mounted in the base of both weir boxes on stainless-steel posts and linked to a Campbell Scientific CR23x data logger (Figure 2.5). The transducers were used to determine the water stage above the discharge orifice, thus allowing discharges and total stormwater volumes to be calculated. The data logger was programmed to record water levels every 20 minutes during quiescent periods and every 30 seconds during storm events. Stage within the control weir was used to trigger the higher sampling frequency during storm events. A Texas Electronics TR525M tipping-bucket rain gauge located within the test plots was also linked to the same data logger so that local rainfall and runoff relationships from the test plots could be established.

Weir discharges, q, were calculated using the known orifice size and the weir stage:

$$q = C\,A\,\sqrt{2\,g\,h} \qquad (1)$$

where q is the weir discharge (cm^3/s), C is the dimensionless orifice coefficient, $g = 9.87\ m/s^2$ is the gravitational constant, h is the weir stage (cm), and A is the cross-sectional area of the weir orifice (cm). The orifice coefficient, C, was calibrated using the observed runoff volume from the control plot and the observed volume of precipitation as determined by the tipping-bucket rain gauge, less a storage volume of 5 mm to account for rooftop interception. The orifice area, A, was calculated using:

$$A = \begin{cases} \pi\, r^2 & \text{outlet flooded} \\ \beta\, r^2 & \text{outlet partially flooded} \\ 0 & \text{outlet dry} \end{cases} \qquad (2)$$

where $\beta = \pi + \alpha\sqrt{1-\alpha^2} - \cos^{-1}\alpha$ and $\alpha = h/r$ account for the effects of partial submergence of the outlet.

Storm events were continuously monitored for a thirteen-month period, from November 1, 2003, to November 30, 2004. Individual storm events were required to have an antecedent quiescent (dry) period of 24 hours (EPA, 2002). Storm peak discharges, q_p (L/s), were obtained using the maximum of the 30-s observations for each storm event. Rainfall intensities were calculated using five minute time steps.

Time to peak discharges, t_p, were found by first determining the precipitation centroid, or depth-weighted time:

$$t_p = \frac{1}{P}\sum_{i=1}^{n} P_i \, t_i \qquad (3)$$

where P is the total storm precipitation depth (cm), n is the total number of time intervals where precipitation was observed during the storm, P_i is the depth of precipitation during the interval (cm), and t_i is the observation time (s). The time-to-peak discharge centroid was also calculated using this method. The resulting peak discharge lag was found by subtracting the precipitation centroid from the runoff centroid.

Curve Number Determination

A commonly used hydrologic model for determining the volume of stormwater runoff is the Curve Number (CN) method. The method provides an estimate of the stormwater runoff depth - equal to the stormwater volume divided by the plot area - for a range of precipitation inputs:

$$\frac{Q}{P_e} = \frac{F}{S} \qquad (4)$$

where Q is the total stormwater runoff depth (cm), S is the maximum soil moisture storage (cm), P_e is the effective precipitation depth (cm), and $F = P_e - Q$ is the abstraction depth (cm). The effective precipitation depth is found using $P_e = P - I_a$ where $I_a = \alpha S$ is the initial abstraction (cm), and where it is commonly assumed that $\alpha = 0.2$. This value was used in the storage calculations.

The curve number is commonly related to S using the equation:

$$CN = \frac{1000}{S + 10} \tag{4}$$

where S is in units of inches. Curve numbers are commonly assigned to land uses according to their runoff characteristics, with impervious areas such as rooftops typically assigned a value of CN=98. A regression method, shown in the Appendix, was used to estimate the maximum soil moisture storage.

Results

A total of 31 storm events were recorded between November 1, 2003, and November 30, 2004 (Table 2.1). A typical rainfall-runoff response is illustrated as Figure 2.6 for a storm that occurred on September 27, 2004. The sample hydrograph illustrates how the amount of runoff from a green roof differs from the black roof over the duration of the storm event. The first runoff peak resulting immediately after the onset of rainfall is clearly seen from the black roof while the green roof shows little response.

Stormwater Retention

Storm hydrographs from the green roof consistently displayed similar retention, or abstraction, characteristics where the initial rainfall was held until the growing medium reached a point near saturation. The black roof produced substantially greater runoff volume during this same initial period. The runoff behavior from both the green and black roofs looks relatively similar once the growing media reached saturation.

Green roof stormwater retention ranged from 39 to 100% with an average retention just under 78% (Figure 2.7). Nearly all of the storm events with precipitation depths smaller than

1.27 cm retained over 90% of the incident precipitation. One storm (3/20/04) with 0.41 cm of precipitation retained 100%. The smallest retention, expressed as a percentage, occurred during a 5.38-cm storm event on 11/19/03 where 39% of the stormwater was retained. These retention values are greater than reported by VanWoert et al. (2005), which may be due to the use of deeper growing media.

An inverse relationship exists between the depth of rainfall and the percent of the storm that is retained (Figure 2.8) with small storms (<2.54 cm) being nearly 88% retained, medium storms (2.54 - 7.62 cm) being over 54% retained and large storms (> 7.62 cm) being nearly 48% retained.

Peak Discharge Attenuation

An important objective in stormwater management is the reduction of peak discharges. A reduction in the peak discharge could enable a reduction in the size of conveyance structures, or provide capacity for conveying stormwater from new development.

Figure 2.9 presents peak discharge data for both the green roof and black roof plots as a function of precipitation depth. Note that while the peak discharge rate for small storms is much lower for the green roof than for the black roof, this effect is reduced for larger storms. Also note that while the peak discharge rate tends to increase with increasing precipitation depth, this is not always the case. Some larger storms have lower peak discharge rates (for both green and black roof plots) than intermediate storms. Time lags associated with peak runoff rates from both rooftops relative to peak rainfall introduces additional complexity in this relationship.

Figure 2.10 presents the scatter plot between precipitation depth and the ratio between peak discharges for the green roof and black roof. Note that the green roof peak runoff is less than the black roof in all but one case. Also note that the runoff ratio increases as the precipitation depth increases. This increased runoff ratio could be attributed to increased water content within the soil media, leading to increased runoff rates. While precipitation depth was the best predictor of the runoff ratio, the peak flow delays from the green and black roofs relative to rainfall peak flow were also significantly correlated to the runoff ratios ($p < .05$). In every case, however, precipitation intensity was found to not be correlated with the runoff ratio ($p >> .05$) and is unlikely to be a factor in determining the stormwater retention performance of the green roof.

Stormwater Detention

Yet another measure of stormwater control effectiveness is the ability to detain, or delay, stormwater runoff. Delaying the stormwater peak allows for greater flexibility in designing stormwater detention facilities, and for desynchronizing stormwater flows. Figure 2.11 presents a histogram of time-to-peak differences between green roofs and black roofs. Note that green roof's runoff peaks are generally delayed relative to black roofs. Only two peaks on the green roof preceded black roof peaks, while most (57%) were delayed between 0 and 10 minutes. The longest delay was approximately two hours. The fact that delays vary from storm to storm can be attributed to large variations in precipitation intensity during a storm as well as antecedent soil moisture conditions, leading to complex runoff behavior.

For the observed data, the average time-to-peak for the black roof was 17.0 minutes, while the average for the green roof was 34.9 minutes, an increase of 17.9 minutes or approximately double the black roof response time. These numbers are somewhat biased by a few storms with long times. The median time-to-peak is shorter, 12.9 minutes for the black roof, 23.1 minutes for the green roof. The median difference between the green roof and black roof peaks is also substantially less, 6.2 minutes, than the average difference. Regardless of which metric is used, green roof response times are substantially lengthened when compared to the black roof responses.

Curve Number Determination

Figure 2.12 presents the observed relationship between runoff depth, Q (cm), and precipitation depth, P (cm). Also plotted are the lines of equal curve number. The average curve number for these data is 86, which was obtained by estimating the maximum depth of moisture storage, S = 4.27 cm, as shown in Figure 2.13 using the best-fit line to the data for each storm event. Other land coverages with similar curve numbers include cultivated land without conservation treatment, and pasture land in poor condition (ARC, 2001).

The maximum water holding depth, S = 4.27 cm, when divided by the depth of the soil, 7.62 cm, yields the total porosity of the medium, n = 56%, which is consistent with the type of soil material used. Also, the conventional curve number approach assumes that the initial abstraction to be $I_a = 0.2\ S = 0.85$ cm, which is consistent with observed data.

Discussion

While modern green roof technology has existed in Europe for decades and is beginning to see widespread use in North America, few studies have quantified stormwater retention ability of green roof systems. One possible explanation for this is the difficulty in experimentally designing and monitoring large field test plots. In order to be cost-effective, even for relatively small storm events, the volume of stormwater shed by 43 m^2 test plots demands a monitoring system which allows flow-through, not complete containment of the runoff.

Also, the relatively novel nature of green roofs in the construction industry creates a number of educational barriers for new installations. Uncertainty exists about how durable the roof's waterproofing layer may be when covered in vegetation and building owners may be hesitant to install a green roof system for fear of leaks. While an improperly installed system, like any new roofing installation, has a leakage potential, vegetated roofs systems are engineered systems designed to drain completely so there is no standing water on the waterproofing membrane. In fact, waterproofing layers in green roof systems in Germany have lasted over 90 years, and most modern green roofs are expected to last at least 50 years as the vegetation shields the roof deck from harmful ultra-violet radiation which breaks down the waterproofing material (Porsche and Kohler, 2003). Additional structural loading may be another deterrent when deciding on whether or not to install a green roof. When saturated, this study's green roof system added approximately 118.06 kg/m^2 which is slightly higher, but comparable to, gravel ballast which weighs anywhere from 48.39 kg/m^2 to 96.77 kg/m^2 (American Hydrotech Inc., 2002).

This study found the use of a two-stage riser system to be sufficiently sensitive to small rainfall events and able to accommodate large storm events as well. The use of an open orifice design led to some challenges during calibration, however, as the calculations needed to convert water level height into flow and volume measurements became exceedingly complex. Other researchers have used a v-notch weir for runoff measurements and this may help to simplify the calibration process (Moran, 2004). This study also found that using a control and experimental plot design was helpful to determine the relative green roof runoff measurements rather than solely relying on one large vegetated system in isolation.

The stormwater retention performance data demonstrated important features of thin-layer green roof systems. First, the roof retained nearly all of the rainfall from most frequent, smaller storm events. This initially could be viewed as a detriment to the watershed as the water cycle is disconnected at this point and streams lose what, in a forested watershed, would be infiltrated rainfall translating over time into sustained stream baseflow (Dunne and Leopold, 1978). In highly urban environments, however, the vast majority of this rainfall does not infiltrate and return to the stream slowly as baseflow, but is transported quickly to the receiving water body and results in flashy, elevated stormflow and the direct transport of urban pollutant loads even after small rainfall events (Schueler and Brown, 2004). For this reason, retention and use of this rainfall by the vegetation is considered a benefit.

A second feature is that the majority of stormwater retention occurs at the beginning of storms as the growing media absorbs the initial amount of rainfall until it reaches saturation at which point the black and green roof hydrographs look relatively similar (Figure 6). This indicates that the roof operates essentially as a retention instrument for a particular water volume rather than detaining and slowly releasing stormwater after percolation through the soil. The green roof system used in this study has porous growing media and a synthetic drainage mat and water retention fabric which allows the media to drain and water to runoff during large events, but may retain most of the residual moisture released from the soil after the rainfall is complete.

Finally, seasonal factors play a large role in how retention occurred in these thin-layered systems. Temperature affects the amount of moisture found in the soil because evapotranspiration is a substantial cause of soil drying. Climates with warmer summers should expect to see higher retention and peak flow reduction during these warmer periods. The timing and duration of storm events also affect retention performance. Intense thunderstorms which commonly occur during the summer in northeast Georgia can produce substantial runoff in highly urbanized areas, even if the total storm volume is relatively small. Green roofs perform best at mitigating the peak flows during these smaller storms. Climates which do not experience such seasonal fluctuations may not exhibit similar variation in retention performance.

Green roofs, while clearly effective at reducing peak flow rates, may be more accurately considered an abstraction BMP where the retained stormwater is transferred back to the atmosphere through evapotranspiration and never reaches the receiving water body. This type of complete retention avoids the elevated flow duration problem found by simply keeping peak flows below a pre-determined level. This BMP is similar in many ways to rain tanks or stormwater cisterns used in stormwater reuse management plans (Mitchell et al., 2001). The obvious difference is that rather than being used consumptively by humans, the flora and fauna on the roof surface are the only organisms directly utilizing the stormwater retained on the roof's surface. An important benefit is that increased evapotranspiration rates may result in substantially lower surface and air temperatures due to latent heat conversion.

Stormwater managers need to consider the effect of green roofs on local hydrology when incorporating them into stormwater management plans. Green roofs may not be a practical stormwater management tool in suburban residential developments where natural watershed hydrology is relatively intact and runoff from rooftops can be easily infiltrated. When there is more intense development in an area, as in a business park, industrial complex or urban in-fill project, green roofs may effectively be used to keep the site's runoff hydrograph from becoming dominated by stormflow.

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Conclusions

Green roofs are shown to be an effective tool for providing stormwater control at the roof scale, particularly for small, frequent storm events in northeast Georgia. Retrofitting existing buildings with a green roof can substantially reduce and - in some cases - eliminate the stormwater contribution from the existing structure. As more test sites are constructed and monitored over time, a more extensive data set may not only demonstrate the feasibility of green roof implementation, but fine-tune green roof performance standards for incorporation into the national BMP database.

For infill projects where complete retention of small storms is required, there is great potential for green roofs. Innovative stormwater management techniques are attempting to recreate the pre-development hydrograph by using a variety of tools rather than simply relying upon one retention pond or stormwater BMP to accomplish the retention goal (Villarreal et al., 2004). In these management scenarios, each impervious surface or cluster of surfaces is considered as a small watershed and retention, primarily using infiltration BMPs, occurs at this microwatershed scale (Echols, 2002). Green roofs could be incorporated into such development scenarios as abstractive BMPs, eliminating a portion of stormflow from the water cycle.

A first step in rehabilitating aquatic ecosystems affected by urbanization is to examine the hydrologic characteristics in the watershed and determine the tools necessary to lessen the impact that altered hydrology has on receiving water bodies (Booth et al., 2004; Riley, 1998). One way to accomplish this is to reduce the amount of impervious surfaces found in the watershed. Green roofs can replace a surface typically seen as a contributor to stormwater problems and cause of urban stream degradation. For architects, this enables them to build stormwater management into their building designs. Engineers may use this abstractive function of a green roof to reduce conveyance-oriented stormwater infrastructure. Planners and watershed managers may use the generated green roof Curve Numbers in future watershed development scenarios.

Table 2.1. Data summary for precipitation (P), green roof (GR), and black roof (BR) hydrologic behavior.

Date	Depth (cm)		Time to Peak (min)			Peak Discharge (L/s)		
	P	GR runoff	GR - P	BR - P	GR - BR	GR	BR	GR / BR
11/19/2003	5.38	3.27	183.09	133.16	49.93	0.56	0.5 3	1.07
2/6/2004	2.69	1.32	74.95	-44.90	119.85	0.21	0.23	0.93
2/12/2004	2.92	1.55	84.65	-37.79	122.44	0.22	0.24	0.94
3/6/2004	0.38	0.01	18.46	11.66	6.79	0.02	0.16	0.12
3/20/2004	0.41	0.00	-	108.15	-	0.00	0.19	0.00
3/30/2004	1.47	0.22	154.76	81.20	73.55	0.03	0.30	0.11
5/12/2004	0.33	0.01	4.18	3.80	0.38	0.01	0.08	0.18
5/16/2004	0.28	0.01	6.51	6.31	0.20	0.02	0.08	0.21
5/22/2004	0.58	0.04	14.82	8.71	6.11	0.03	0.16	0.19
5/31/2004	1.45	0.55	32.84	24.62	8.22	0.24	0.52	0.45
6/9/2004	5.97	2.36	13.62	17.81	-4.18	0.99	1.31	0.76
6/18/2004	0.66	0.02	7.41	6.51	0.90	0.03	0.50	0.06
6/21/2004	0.30	0.01	9.83	7.53	2.30	0.02	0.10	0.22
6/22/2004	0.30	0.03	1.76	1.63	0.13	0.02	0.06	0.30
6/23/2004	0.81	0.09	33.27	26.96	6.31	0.03	0.29	0.09
6/25/2004	0.69	0.03	14.37	10.79	3.57	0.04	0.70	0.06
6/27/2004	3.53	1.13	28.78	18.53	10.25	1.11	1.31	0.84
7/26/2004	3.58	1.25	31.66	20.42	11.24	0.71	1.33	0.54
7/30/2004	1.47	0.13	11.56	9.25	2.31	0.23	1.29	0.18
8/5/2004	2.06	0.44	9.16	7.63	1.53	0.69	1.30	0.53
8/12/2004	5.36	2.68	33.38	18.12	15.26	0.38	0.41	0.93
8/20/2004	1.45	0.31	12.63	6.63	5.99	0.21	0.82	0.26
9/2/2004	0.94	0.18	37.56	27.39	10.17	0.06	0.15	0.41
9/6/2004	8.23	4.43	37.88	14.18	23.70	0.23	0.26	0.87
9/27/2004	8.43	4.26	54.43	20.06	34.37	0.22	0.25	0.88
10/12/2004	0.91	0.10	10.54	5.62	4.93	0.05	0.58	0.08
10/19/2004	1.50	0.39	24.79	16.41	8.39	0.05	0.13	0.41
11/3/2004	3.84	0.82	21.50	18.27	3.24	0.23	0.26	0.89
11/4/2004	1.19	0.26	39.14	36.16	2.98	0.22	0.27	0.82
11/12/2004	2.49	0.45	-66.42	-48.13	-18.28	0.07	0.21	0.31
11/21/2004	0.84	0.10	105.02	81.10	23.92	0.04	0.24	0.18

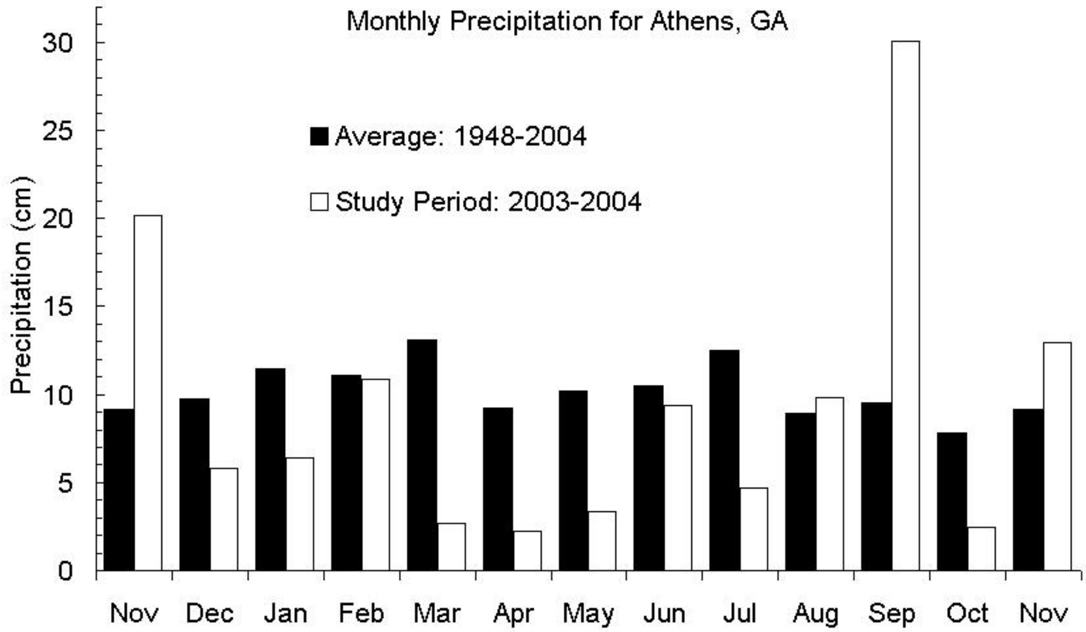

Figure 2.1. Average and study-period monthly precipitation depths.

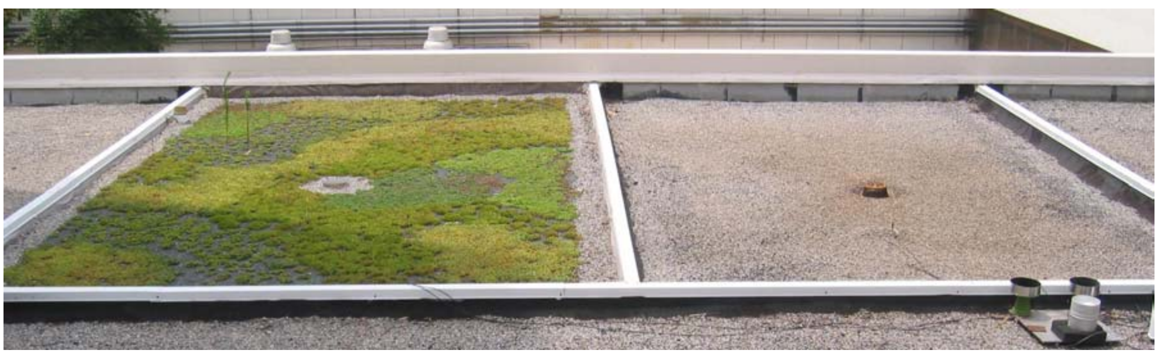

Figure 2.2. Green (left) and black (right) roof stormwater runoff plots.

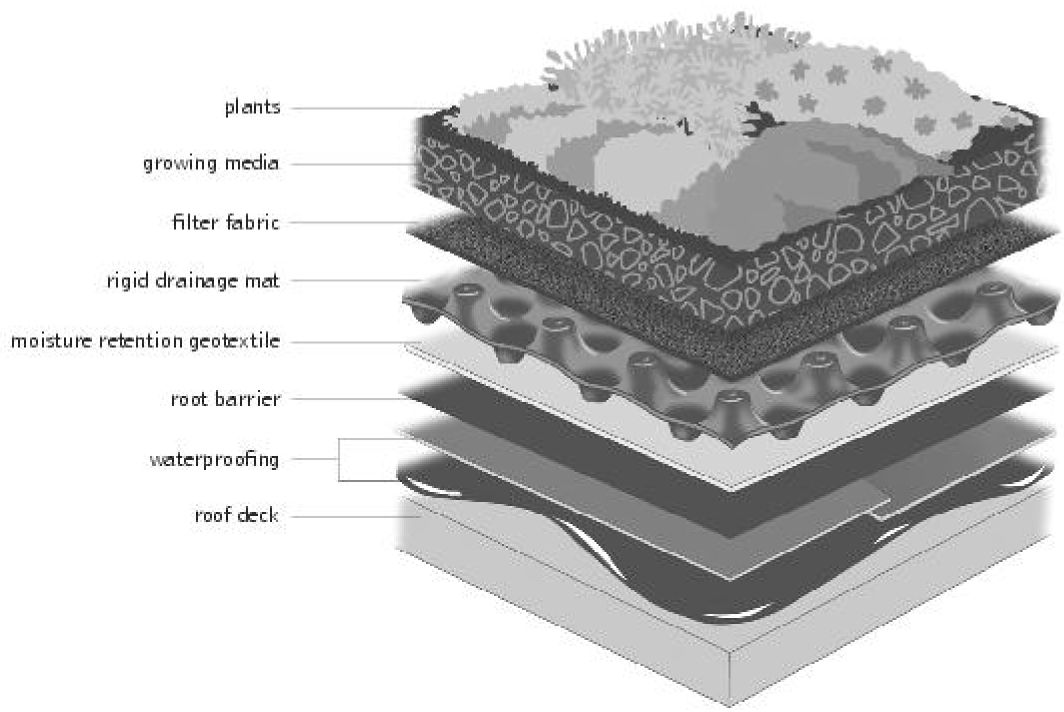

Figure 2.3. Detail of green roof composition used in study.

Figure 2.4. Weir system for monitoring rooftop stormwater runoff.

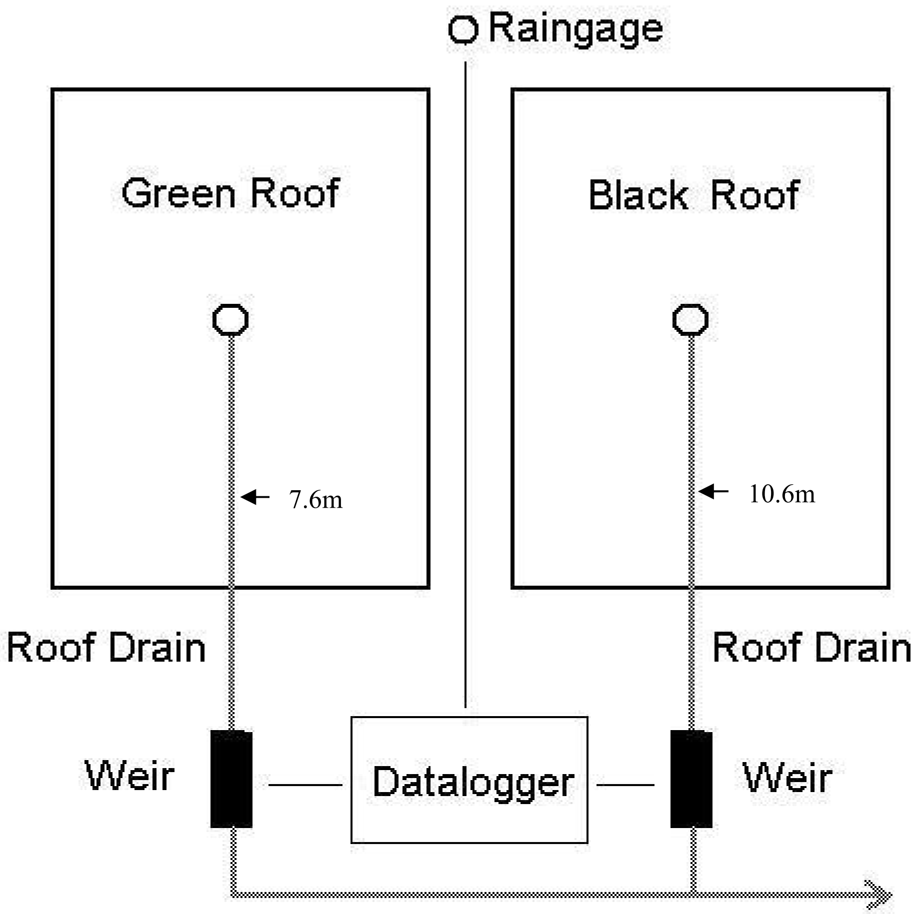

Figure 2.5. Rooftop precipitation and stormwater runoff monitoring system.

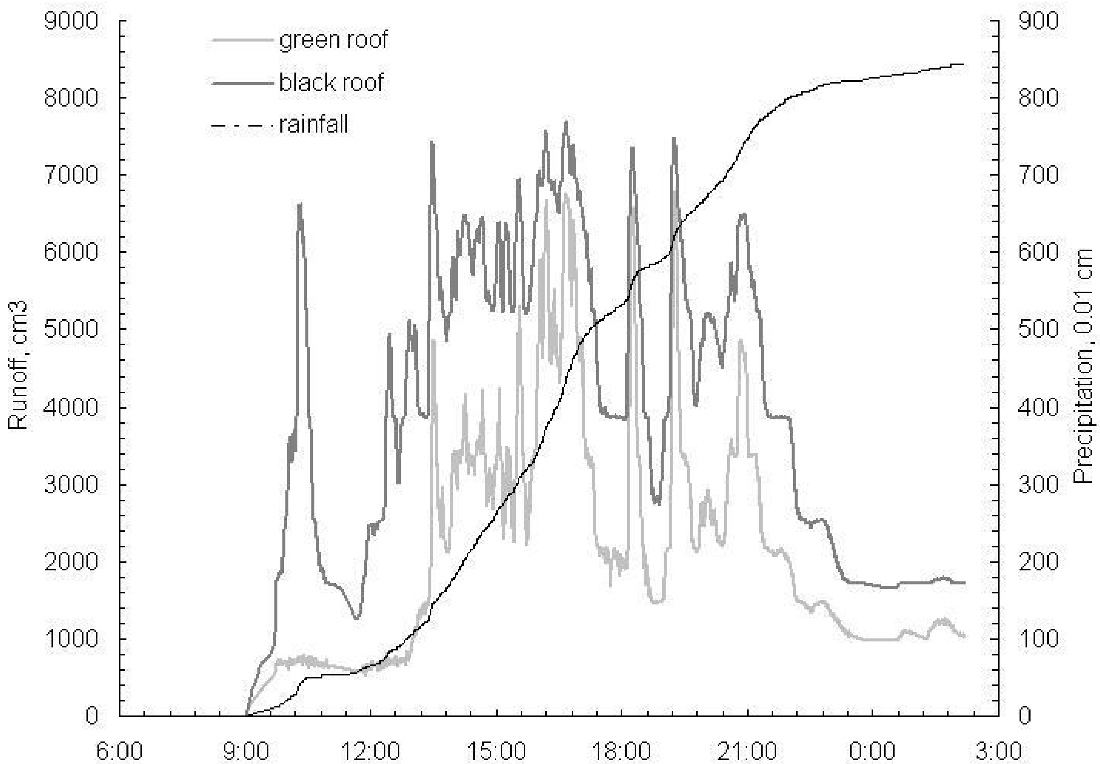

Figure 2.6. Cumulative precipitation depths and runoff volumes from plots for a storm on 9/27/04.

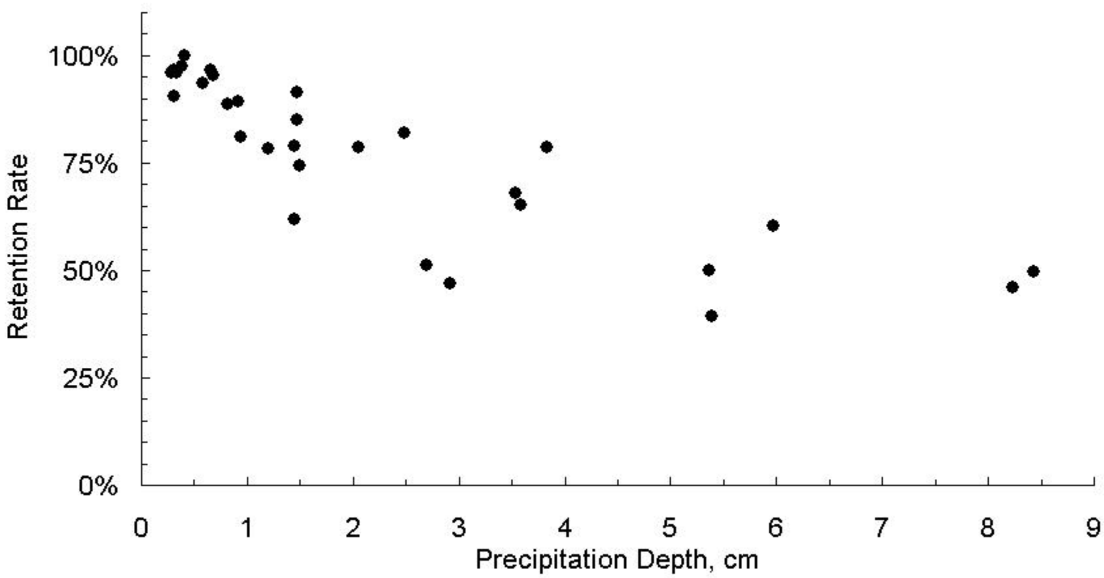

Figure 2.7. Precipitation retention rates as a function of total precipitation depth.

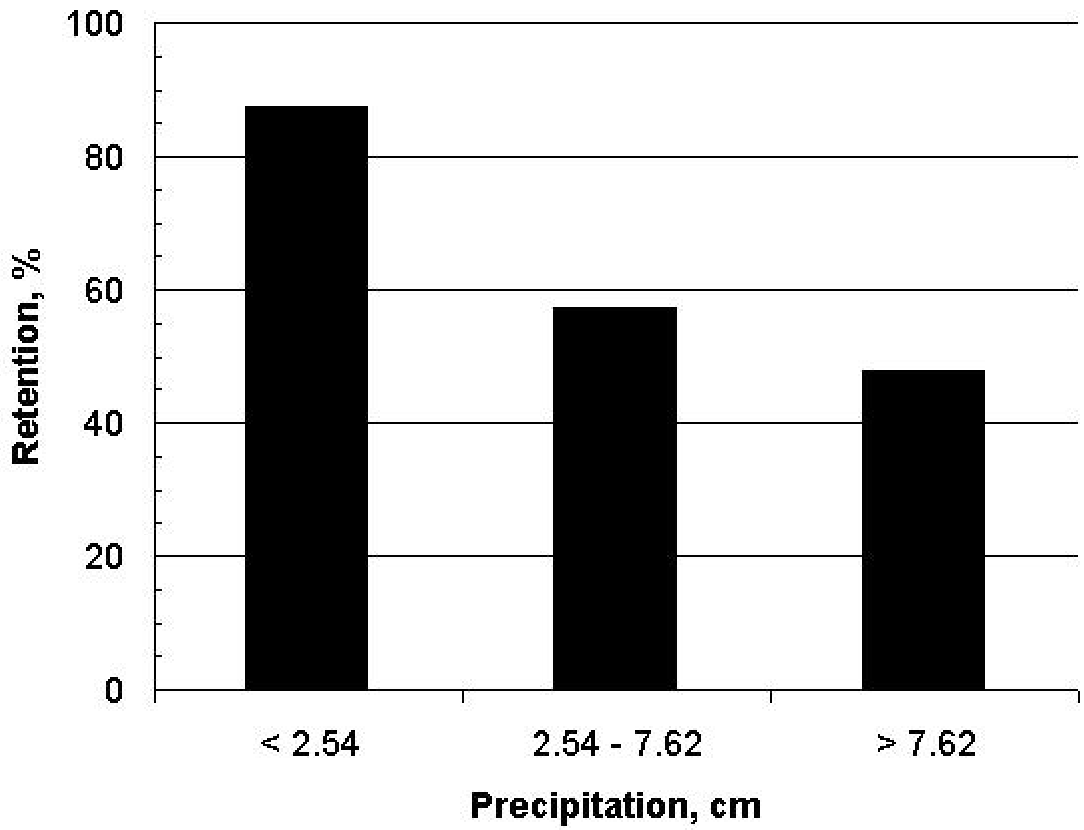

Figure 2.8. Retention rate for three precipitation depth categories.

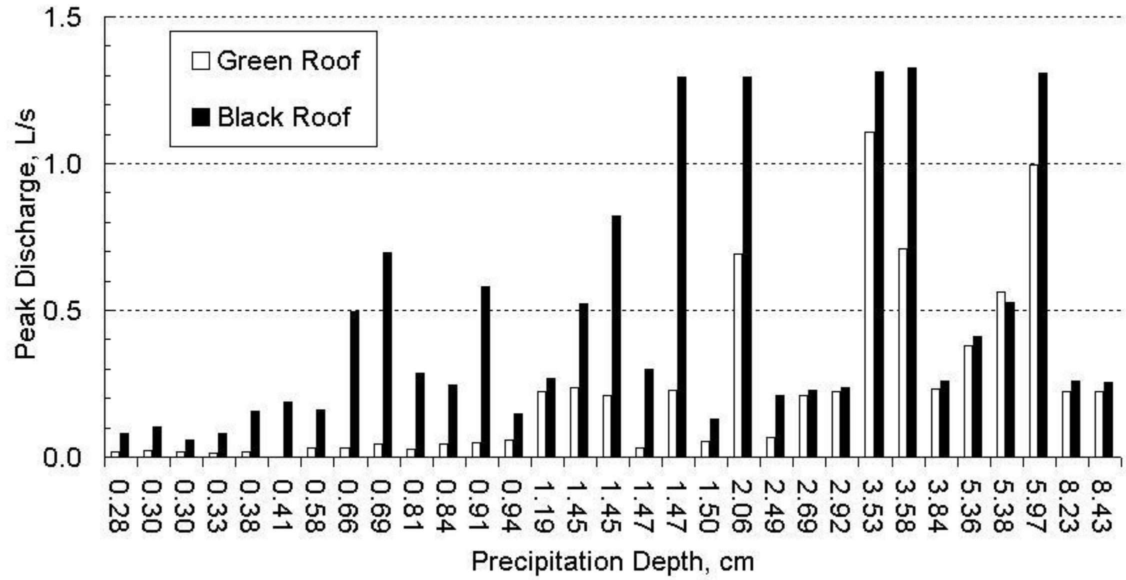

Figure 2.9. Green roof and black roof peak discharge rates as a function of precipitation depth.

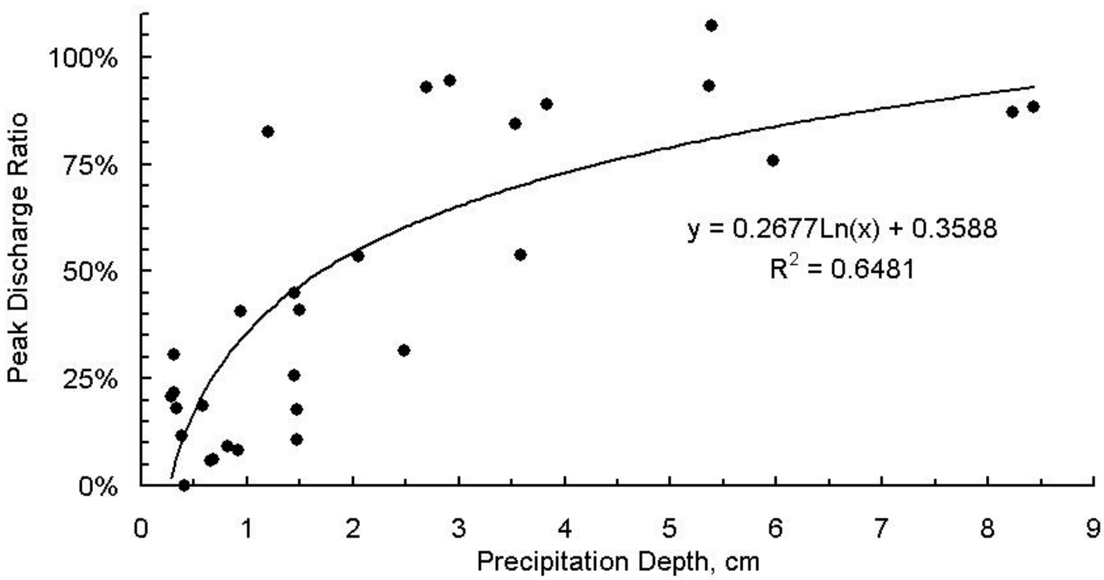

Figure 2.10. Relationship between total storm precipitation and the ratio between green roof and black roof peak discharge rates.

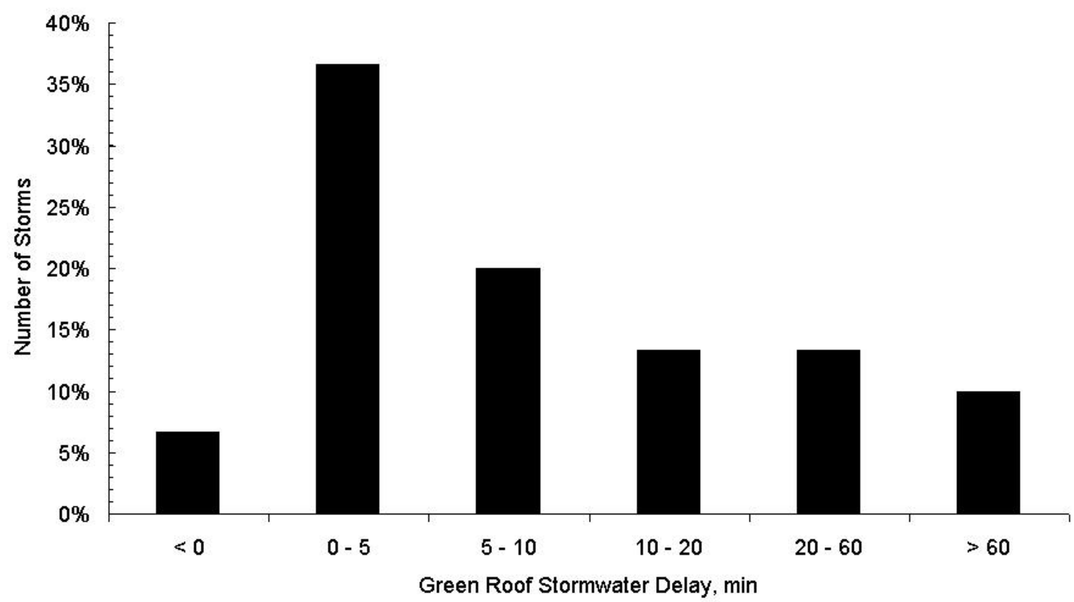

Figure 2.11. Time-to-peak delay between green roof and black roof stormwater responses.

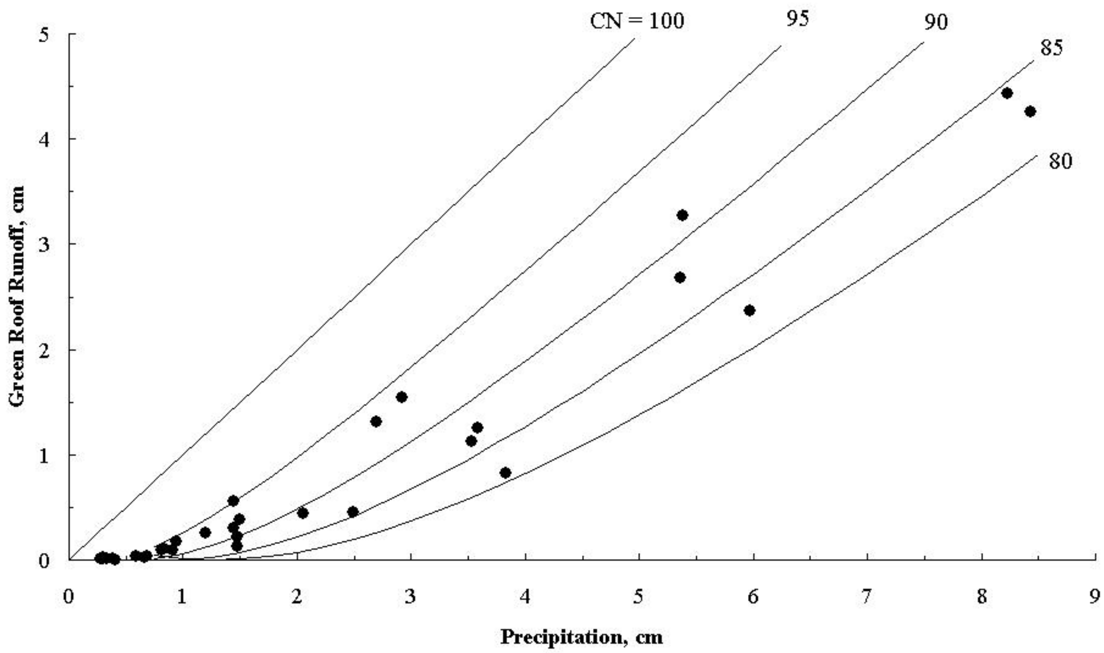

Figure 2.12. Relationship between precipitation and runoff showing lines of equal Curve Number

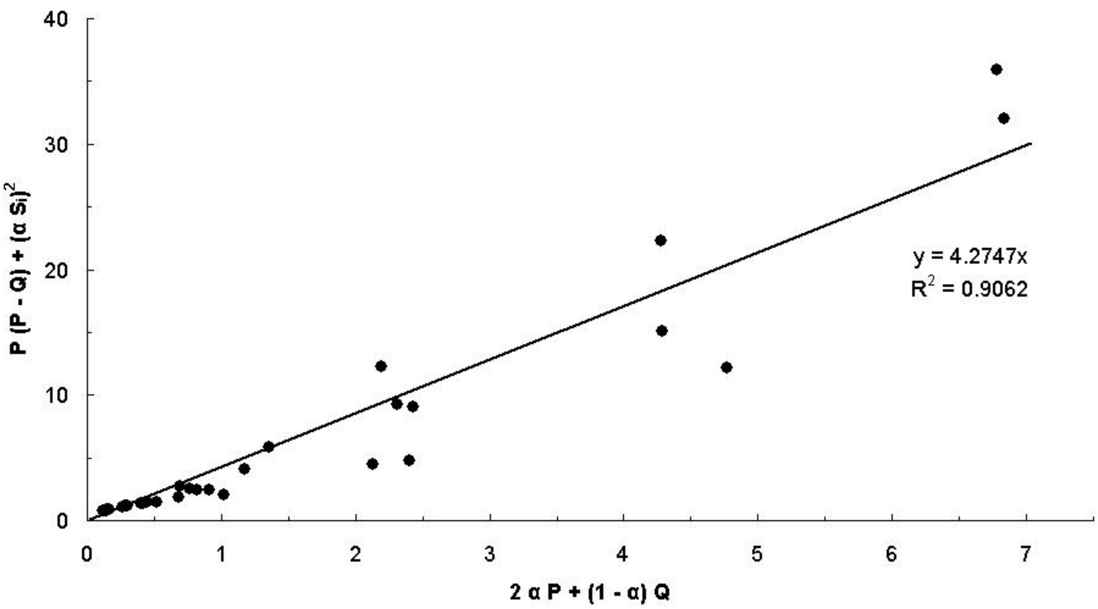

Figure 2.13. Regression method for determining the maximum soil moisture storage, S, which is the slope of the plotted line drawn through the points that represent the value for each storm event.

CHAPTER 3

VEGETATED ROOFS FOR STORMWATER MANAGEMENT AT MULTIPLE SPATIAL SCALES[1]

[1] Carter, T.L. and Jackson, C.R. Accepted by *Landscape and Urban Planning.*
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Abstract

Stormwater runoff from impervious surfaces and other urban land cover is particularly detrimental to receiving water bodies in urban centers. A variety of management practices exist to combat the environmental degradation associated with the altered hydrology in urban areas. Vegetated, or green, roofs are emerging as one of these stormwater management tools in the United States. Investigations have primarily been focused on roof-scale processes such as individual roof stormwater retention, plant growth, or growing media composition. Few studies have examined the impact that widespread green roof application could have on the hydrology of a real-world watershed. Using local green roof stormwater retention data, this study modeled hydrologic effects of green roofing scenarios in an urban watershed at a variety of spatial scales. A detailed spatial analysis demonstrated areas of the watershed where green roofs would significantly reduce the total impervious area and provide additional stormwater storage. Hydrologic modeling demonstrated that widespread green roof implementation can significantly reduce peak runoff rates, particularly for small storm events. This analysis recommends the use of vegetative roofs as an abstractive stormwater best management practice in urban watersheds to replicate the interception and evapotranspiration aspects of the water cycle found in less disturbed environments.

INDEX WORDS: hydrology, green roof, urbanization, best management practice

Introduction

Urbanization and the increase in impervious surfaces typically associated with urban development have consistently been shown to result in degraded aquatic ecosystems (Miltner et al., 2004; Wang et al 2001). These effects are a function of increased stormwater runoff volumes across a watershed due to the efficient routing of stormwater off impervious surfaces and into a storm sewer system that ultimately discharges into a receiving water body. These elevated volumes impact stream ecosystems through amplified flow rates which increase bed and bank erosion (Wolman, 1967), increased frequency of disturbance (Booth and Jackson, 1997), rapid and efficient pollutant transport (Olguin et al, 2000; Sutherland et al, 2002) and an increase in nuisance flooding in urban watersheds (Niezgoda and Johnson, 2005). Cumulatively, the effects of impervious surfaces found in urban areas have recently been called the "urban stream syndrome" (Walsh et al, 2005b).

A number of policy tools have been implemented to reduce the impact that impervious surface has in urban watersheds. One strategy is to place a limit on the amount of total impervious area (TIA) in a given watershed. Schueler (1994) developed the Impervious Cover Model (ICM) which identified a threshold of 10% impervious cover at which point streams become impacted and a threshold above 25% impervious cover where the stream quality is considered "non-supporting" for aquatic life. Local governments commonly execute this standard in water supply watersheds where preservation of water quality in a reservoir is important to the longevity of an urban area's water supply. The Georgia Planning Act of 1989, for example, limited impervious area in small water supply watersheds to 25%, or existing use, whichever is greater (Georgia DNR, 2005).

There are a number of problems with setting a limit on impervious surfaces in urbanized watersheds. Since land is valuable due to development pressure, limiting developable area is often politically unfeasible due to conflicting economic interests. Existing land use in urban centers often exceeds the 25% impervious threshold. Finally, the TIA threshold approach treats all impervious surface areas equally. Researchers have used the metric of "connected" or "effective" impervious surface area (EIA) to describe the aspects of impervious cover which drain directly into a storm sewer system (Alley and Veenhuis, 1983). EIA is more closely correlated to elevated pollutant loads (Hatt, 2004), elimination of sensitive taxa of macroinvertebrates (Walsh, 2004) and a better explanatory variable for an endangered fish species (Walsh et al., 2004) than TIA.

An alternative approach to limiting impervious area has been instituted through the National Pollutant Discharge Elimination System (NPDES) permitting requirements under the Clean Water Act. This strategy encourages stormwater managers to reduce the environmental impact of stormwater from impervious surfaces through the use of stormwater best management practices (BMPs). Stormwater BMPs are primarily designed to lessen the impact of development on receiving water bodies in urban or urbanizing areas through increasing stormwater storage areas across a watershed, slowing the flow of water into a receiving water body, and/or replacing impervious surfaces with pervious areas that allow for stormwater infiltration. This last option functions to reduce the amount of TIA in the watershed.

In highly urbanized watersheds, the amount of land available exclusively for stormwater BMPs is limited, thus creating a need for developed spaces that serve multiple purposes. This involves designing buildings, parking lots and roads that not only serve the needs of the human population, but also perform stormwater management functions. Although rooftops constitute a significant portion of impervious area particularly in highly urbanized watersheds, until recently they have been overlooked as avenues for stormwater management in the United States. Recent studies have begun to document how the use of thin-layered vegetated roof systems allows for rooftops to function both as a structural component of the building envelope, but also as a stormwater management tool (Mentens et al., in press). These studies primarily look at plant growth (Emilsson and Rolf, 2005; Monterusso et al., 2005), optimal growing substrate characteristics (Denardo et al, 2003), or the stormwater retention of small green roof test plots (VanWoert et al, 2005) to create performance standards for individual green roof systems.

Evaluating green roof stormwater retention at the roof scale is a valuable first step in determining green roof application as a stormwater BMP. Another important application for stormwater managers is to know how green roofs can be incorporated into a stormwater management plan in a developed or developing watershed. This involves modeling watershed responses to hypothetical roof greening scenarios. Villarreal et al (2004) demonstrated how green roofs could be used to increase stormwater runoff storage as part of an inner city urban stormwater retrofit project in Sweden. Investigations at a range of spatial scales, from individual roofs to entire watersheds, can provide comprehensive guidance for effective ways to establish green roofs as a viable urban stormwater BMP.

This study examines the effects that vegetated, or green, roofs can have on stormwater runoff volumes at a variety of spatial scales in a highly urbanized watershed in the Piedmont region of Georgia, USA. Our primary goal was to determine what the effect of widespread roof greening would be on the hydrology of a real-world urban watershed using runoff data from an established green roof system. The change in hydrology was investigated at four spatial scales to account for land use diversity within the watershed. We also modeled the stormwater outflow of the receiving water body under hypothetical roof greening scenarios to determine the effect that roof greening has on the flow regime of an urban stream system. Finally, we examined how widespread green roof implementation may be used to accomplish statewide stormwater management goals.

Materials and Methods

Study site

The Tanyard Branch watershed in Athens, Georgia was selected as the test site for the spatial analysis and hydrologic modeling. Athens is located in northeast Georgia, approximately 100 km east of Atlanta. This region of Georgia averages approximately 123.2 cm of rainfall per year with March typically having the highest total rainfall. This 237 ha watershed encompasses much of the University of Georgia as well as the urban center of Athens. Water quality sampling and physical habitat assessment has revealed the second order stream system has been negatively impacted by the effects of urbanization (Herbert et al., 2003).

A green roof test plot was established on the Boyd Graduate Studies building in October 2003 on the campus of the University of Georgia. The test plot uses an engineered system from American Hydrotech, Inc., primarily comprised of loose-laid synthetic specialized layers underneath the growing media and plant material. This growing media is a blend of 55% Stalite expanded slate, 30% USGA sand, and 15% organic matter composed primarily of worm castings. This media has a bulk density of 1.508 g/cm^3 and the total porosity is 50.6%.The soil mix was spread to a depth of 7.62 cm across the plot. Six drought-tolerant plant species were selected for their ability to survive low nutrient conditions and extreme temperature fluctuations found at the roof surface. The species included *Sedum album* “Murale”, *Sedum album* “Jellybean”, *Sedum kamtschaticum*, *Sedum sexangulare*, *Delosperma nubigenum*, and

Delosperma cooperi. The plants were supplied as 3.4 x 3.4 x 6.25 cm plugs which were planted in the growing media at a density of 50 plants/m^2.

A rainfall-runoff relationship for the green roof system was established using 31 storm events over the time period of November 2003 – November 2004. This stormwater retention performance data was used to develop a curve number (CN) of 86 for this green roof system. A detailed analysis of the methods and results from this green roof performance study is currently in press (Carter and Rasmussen, in press).

Watershed application

To establish how widespread green roof performance could affect the hydrology in the Tanyard Branch watershed, detailed spatial analysis was performed and hydrologic modeling methods were employed. The spatial analysis was done using ArcView 3.2, a commonly used geographic information system (GIS) software package (ESRI, 1999). 2003 full color aerial photographs with 0.15 m pixel resolution were obtained from the city of Athens. From these photographs, the land coverage in the watershed was digitized at a scale of 1:500 (Figure 3.1). Land uses were classified as roofs, flat roofs, roads, parking, sidewalks, sport fields, or landscaping. Ground-truthing was also performed where the authors randomly selected parcels on the aerial photographs and confirmed the classification on the ground to ensure they were accurate. Total impervious area (TIA) as well as existing pervious areas (landscaping) were then calculated based on the digitized land coverages. This detailed spatial information allowed for different green roofing scenarios to be explored across the watershed.

Stormwater runoff modeling

The Soil Conservation Service (SCS) curve number method was the infiltration and runoff model chosen due to its simplicity and widespread use amongst engineers and watershed managers. SCS has developed CN values for land uses according to their runoff characteristics. This method is also recommended in the Georgia Stormwater Management Manual for use in urban watersheds of the size of our study area (ARC, 2001). Impervious areas were assigned a CN of 98. A CN of 84 was used for land uses classified as landscaping. The experimentally-derived CN of 86 was used for green roofs.

Runoff modeling was also performed using StormNet Builder, a stormwater modeling software package which uses EPA's SWMM 5.0 analysis engine and CN infiltration method for routing runoff through a watershed (Boss International, 2005). For this watershed routing model, we used five drainage areas as delineated for the composite CNs and land cover as delineated from the aerial photographs. The stormflow was routed between each subwatershed using Kinematic Wave routing and the Manning equation. Model storm events used a type II rainfall distribution for various 24 hour design storms. Runoff was modeled in 15 minute time steps over a two day period. This allowed for total outflow volumes and peak flows to be established under the different watershed development scenarios.

Composite CNs were then established for different roof greening scenarios in the watershed using the spatial information compiled in ArcView and the CNs for each land use type. The percentage of a particular land use was multiplied by the CN for that land use to get a single weighted CN for the evaluated drainage area. The changes in stormwater volume were modeled for three scenarios: existing land cover, all roofs greened, and all flat roofs greened. Five design storm volumes were modeled: a small storm event of 1.27cm, the Georgia Stormwater Manual's water quality event of 3.05cm, the 1 year-24 hour event of 7.92cm, the 25 year-24 hour event of 15.85cm, and the 100 year-24 hour event of 19.51cm. Analysis focused on the smaller storm events as their runoff characteristics have been shown to be most greatly affected by impervious surface cover which is directly connected to the stream system (Walsh et al, 2005b)

Composite CNs were also developed at four spatial scales: total watershed, subwatershed, zoning, and parcel (Figure 3.2). The total watershed scale evaluates all of the land in the Tanyard Branch watershed as one drainage area. Subwatersheds were delineated using a watershed delineation extension in ArcView (Olivera, 2005) The five resulting subwatersheds were identified for individual analysis. Zoning maps were obtained from the city of Athens and each zoning block was delineated and analyzed. Finally, five parcels were randomly selected within each zoning block. The land area containing the University of Georgia is not subdivided into parcels and therefore no parcel analysis was done on campus property. In the other zones, however, the parcels were evaluated individually for their stormwater contribution.

<u>Results</u>

Spatial analysis

Spatial analysis revealed that 53.8% of the Tanyard Branch watershed is covered in impervious surface. As the level of spatial resolution increases, the amount of imperviousness becomes more widely varied between the drainage areas. Areas zoned residential ranged from 35-45% TIA while commercial areas fell between 54-78% TIA. When evaluating the commercial parcel land coverage, however, the range of TIA swung widely from a high of just over 92% TIA to a low of around 17% TIA (see Appendix B for complete list).

Roofs accounted for 15.9% of the total land cover and 29.5% of impervious surfaces in the watershed. When evaluated at the zoning level, rooftops constitute less proportion of the TIA in commercial areas versus residential areas, although the amount of flat roofs in the commercial and downtown areas are significantly higher than in areas zoned residential. Parcel data again showed a wide range of rooftop impervious area in the commercial areas with coverage ranging from 0-89% of the total impervious area in the parcels. Rooftops in single family residential areas are nearly always the largest amount of impervious surface in the parcel and often over 65% of the TIA in the parcel. Slightly under half of the roofs in the watershed (47%) are flat roofs. Flat rooftops are concentrated in the downtown and commercial areas constituting anywhere from 25-85% of the rooftop coverage in these areas. As expected, residential zones contained few flat roofs with zones ranging from slightly over 8% to 0% flat rooftop coverage.

At the zoning scale, reductions in TIA are evident with both roof greening scenarios depending on the zoning class (Figure 3.3). In some residential cases, greening all the rooftops drops the TIA from above 37% to below 20%. This drop would change the area from a "non-supporting" watershed to one that was simply "impacted" according to the impervious cover model (CWP, 2003). Other zoning areas show significant differences in TIA reduction depending on whether all roofs are greened or only flat roofs are greened. Commercial-downtown (c-d), commercial-general (c-g), and government (g) have the largest potential for TIA reduction if only flat roofs are considered as viable candidates for greening.

CN modeling

Complete runoff values for all five design storms from existing land use and both roof greening scenarios are found in Tables 3.1 and 3.2. As design storms increase in size, runoff volumes increase and concomitant volume reductions from green roof scenarios are diminished. This expected decline in retention results from the green roof reaching field capacity then quickly releasing the excess rainfall from larger storm events similar to conventional roofs.

The composite CN for existing land use at the watershed scale is 92 corresponding to 2.35 cm of storage volume across the watershed according to the SCS model. For this condition, the smallest design storm of 1.27 cm produces 0.481 ha-m of runoff. When all the roofs in the watershed are greened, the composite CN is reduced to 90 and the runoff volume for the 1.27 cm storm event drops to 0.304 ha-m. This is a 36.9% reduction in runoff volume. When only flat roofs are greened, the resulting composite CN is 91 and the runoff volume for the 1.27 cm storm event is 0.391 ha-m, an 18.9% reduction in runoff volume (see Appendix C for complete CN breakdowns).

Using the existing land use CN for the largest design storm of 19.51cm produces 40.126 ha-m of runoff. When all the roofs in the watershed are greened, the runoff volume for this design storm drops to 38.774 ha-m, a 3.4% reduction in volume. When only flat roofs are greened, the runoff volume for this design storm is 39.490 ha-m, a 1.6% reduction in volume. Disaggregating CN analysis at the four spatial scales results in greater fluctuations in runoff volumes according to watershed location and amount of TIA found in each grouping. At the subwatershed (SW) level the primary differences are seen when the two green roofing scenarios are compared. SWs 2 and 5 lose much of their stormwater retention performance when only flat roofs are greened, with runoff reduced from 31% and 36% to 7.7% and 8.3% respectively. Conversely, SW 3 contains all flat roofs and stormwater reductions remained consistent between the all greened and all flat greened scenarios retaining 36% of the 1.27 cm storm event.

Applying green rooftop scenarios according to zoning classification resulted in further spatial clarification than did SW. The top retention values were found for the commercial-downtown (c-d) zone where all roof greening resulted in a 45% reduction in runoff volume for the 1.27 cm storm event and nearly 40% reduction in runoff volume when only flat roofs are greened. Although greening the c-d zone produced the largest amount of stormwater retention for flat roof greening, this result is masked when considering roof greening at the SW level as the entire c-d zone falls in SW 1. SW 1 ranked third in stormwater retention volume for flat roofing scenarios when compared with the other four subwatersheds. C-d, commercial-general (c-g), and government (g) zoning blocks showed the most promise for roof greening under all flat roof greening scenarios.

Residential zoning blocks illustrated the importance of differentiating between flat and pitched roofs when considering roof greening scenarios. In the case of areas zoned single-family residential (rs-5 and rs-8), stormwater volume reductions for the all roof greened scenario was among the highest in the watershed at 47% and 40% respectively. When only flat roofs were considered for greening, retention values dropped to zero in both cases.

Parcel disaggregation demonstrates the extreme variation that exists even within zoning categories. For example, in the zoning block with the highest stormwater retention values, c-d, one parcel retained nearly 91% of the 1.27 cm storm event as over 80% of the site was covered in rooftop. Another parcel in the same zone, however, provided no stormwater retention at all under either roof greening scenarios as the majority of the site was surface parking. The ratio of the amount rooftop to parcel area is important in determining how much additional rainfall storage will be provided from this green roof system. The largest amount of land area taken up by rooftops was 83% in a downtown parcel with the majority of roofs accounting for 10-30% of land area (Figure 3.4).

StormNet Builder modeling

Modeling watershed outflow volumes resulted in significant peak flow reductions when all rooftops were greened in the watershed, particularly for smaller storm events. The 1.27 cm storm event resulted in peak flow volumes of 1.62 m^3/s for existing land uses. Greening all the roofs produced a 26% reduction in peak runoff volumes for the 1.27 cm storm resulting in peak flows of 1.19 m^3/s (Figure 3.5). Greening all the roofs also resulted in a peak flow in the 1 year, 24 hour storm event which was less than the existing 2 year 24 hour storm event peak flow (Figure 3.6) For larger storms, there was less reduction in peak outflows, although the peak outflow of 32.97 m^3/s from greening all the roofs for the 100 year, 24 hour storm was very similar to the peak outflow of 32.23 m^3/s from the existing 50 year, 24 hour storm (Figure 3.7). Greening all flat roofs reduced peak flows by about half as much as greening all roofs, similar to CN results for the watershed scenarios. Green roof implementation did not result in any peak flow lag times occurring across the watershed. There was, however, a slight increase in outflow volumes on the falling limb of the green roof hydrographs.

Discussions and Conclusions

To accurately assess the possibility of implementing green roofs as a stormwater BMP in an urban watershed, detailed spatial analysis needs to be undertaken to direct management efforts. This spatial analysis is best accomplished at a variety of spatial scales to evaluate overall project feasibility in a watershed context as well as individual plot-level scenarios. In the case of the Tanyard Branch watershed, we found high potential to use existing rooftops as stormwater runoff management tools as they constitute significant land area in the highly urbanized watershed. Other studies that disaggregate impervious surface cover in urban areas have typically only focused on a single zoning category such as residential land use and found rooftop coverage to constitute around 1/3 of the impervious surface coverage (Lee and Heaney, 2003). Our spatial analysis revealed slightly less proportion of rooftop impervious coverage across the watershed with minimal variation among zoning categories for the amount of total rooftop coverage. These results can be misleading, however as the majority of areas contain sloped rooftops which are more difficult to vegetate.

When only flat roofs are disaggregated from the spatial data, at the zoning level a clear hierarchy for green roof implementation emerges. The impervious surface cover of three zoning categories is dominated by over 65% of flat rooftops while the remaining five zones contain impervious areas with less than 26% flat rooftops and a median flat roof percentage of 3.4%. The three zoning categories with most flat roof space are commercial areas and area upon which the University of Georgia is located which contains many institutional buildings and large dormitories. No industrial sites are located in the watershed. Residential sections of the watershed show little opportunity for flat roof greening. If the flat green roof scenario is considered the most practical for implementation, then areas zoned commercial, industrial, or institutional centers which are known to contain large flat-roofed buildings should be targeted for retrofit installations. In the Tanyard Branch watershed, 50.6% of the land area fit into these categories. When low impact development modeling scenarios are only centered on residential application (see Brander et al, 2004), there is little opportunity for practical green roof implementation. Evaluating all zoning classes, however, provides a convenient scale to analyze green roof implementation feasibility as the distinguishing features of each zoning class are directly related to the size and shape of rooftop.

Changes in hydrology due to green roofing scenarios are clearly dependent upon the size of design storm event. Even with widespread green roof installation, change in hydrology across the watershed will be minimal for storm events greater than the 2 year, 24-hour event. In Athens, however, over 60% of storm events throughout the course of a year in Athens are 1.27 cm or less and over 80% are less than 2.54 cm (Figure 3.8). For these smaller events across the watershed, the modeled results have a more noticeable effect on recommended treatment volumes. For example, the Georgia Stormwater Manual recommends interception and treatment of all the runoff from 85% of the storms that occur during the course of a year. In the case of Tanyard Branch, a volumetric runoff coefficient of .53 is multiplied by the 85th percentile rain event (3.05 cm) giving a water quality volume of 3.85 ha-m. Green roofs would retain approximately 0.54 ha-m or approximately 15% of the volume needed to be intercepted and treated. No "treatment" and re-release is actually occurring on this volume, as the water cycle is short-circuited at the roof.

At the watershed, subwatershed and zoning scale, modeling widespread roof greening illustrates a number of important considerations for implementing green roof systems. The additional storage provided by green roofs in this watershed reduces the total peak outflow volumes in the watershed significantly. This decline in peak flow volume reduces the frequency of the bankfull flow events which may result in changes in bankfull cross-section dimensions originally expanded during urbanization (Doll et al, 2002). For future storm sewer retrofitting options, reductions in peak flow volumes from roof greening could provide economic benefits through decreasing the sizing of culverts and pipes designed for large storm events. The volume reductions for flat roofing scenarios will primarily come from the zones of the watershed where impervious areas are most directly connected to the storm sewer system. Reducing the stormwater contribution of these impervious surfaces in the watershed is particularly important due to their disproportionate influence on the health of receiving water bodies (Walsh et al, 2005a).

Volume reductions and subsequent stormflow velocity reduction has conflicting implications for pollutant transport and receiving water quality. The green roof retention performance occurs during the early stages of rainfall as the well-documented "first flush" phenomenon (Sansalone and Cristina, 2004) transports the majority of toxicants into storm sewer systems. With lower runoff velocities, larger particles to which certain pollutants are bound may not be moved into the storm sewer system during the rising limb of the storm event. Conversely, the operationally dissolved fraction of pollutant loads will be transported to the system in higher concentrations as they move easily even with reduced volumes of runoff. The areas where roof greening will be most effective are also the areas where the largest concentrations of vehicular-related pollutants occur. These factors may result in a focused pulse of toxicants during the early stages of a storm event with lower runoff volumes.

For individual parcels, the ratio of rooftop coverage to parcel area is the most important factor in determining where to install green roof systems. Since green roofs serve to store water and release it into the atmosphere through evaporation or transpiration, they function as the interception mechanism found in forested sites. Interception values for urban forests have been reported as 1.6% of total rainfall (Xiao, 2002). For nearly all parcels, this interception value was met through the use of green roofs for all storms including the 100 year, 24 hour storm event interception value of 0.31 cm. Other management goals may wish to be met at the parcel level. The initial abstraction value in the curve number method, for example, is a volume designed to replicate interception, evaporation, initial infiltration, and surface depression before runoff begins. When roofs cover over 30% of the site, this initial abstraction value for forested conditions is met. Depending on the goals of the stormwater management system, various decision-making criteria can be established at the parcel-level to direct implementation efforts. The strong linear correlation between a parcel's rooftop impervious cover and additional water storage makes application of these criteria quite straightforward.

Using the Tanyard Branch watershed as a case study, hydrologic modeling suggests that green roofs alone cannot be relied upon to provide complete stormwater management at the watershed scale. Other studies have examined benefits provided by a variety of source control stormwater management tools similar to green roofs at the scale of a drainage basin or jurisdictional watershed and found that a combination of source control management strategies and water reuse techniques are more cost effective than their traditional centralized counterpart (Coombes et al, 2002). Decentralized stormwater management practices can also be used in conjuction with a tradable stormwater allowance system which produces a low-cost alternative to a single, centralized system (Thurston et al, 2003). To the extent that green roofs can be incorporated into a similar watershed management plan that emphasizes distributed stormwater controls, they may play an important role in areas particularly constrained by existing development and infrastructure.

While roofs constitute nearly 30% of the total impervious area in the Tanyard Branch watershed, the amount of other types of land coverage lessens the hydrologic impact of widespread roof greening at the watershed scale. In watersheds of larger metropolitan areas or industrial sites which contain a proportionally larger percentage of rooftops relative to other land coverage, a different conclusion may be reached. Green roofs do have the potential to replicate portions of the predevelopment hydrograph which may be lost after urbanization, functioning to intercept and evaporate rainfall before it reaches the ground. Using green roofs for this specific task could prove extremely beneficial in highly urbanized watersheds where opportunities for stormwater management are lacking.

Jurisdictions and urban watersheds which have digitized land cover and zoning maps in a GIS may evaluate the potential stormwater benefits from green roof implementation using methods similar to the ones described in this study. Applying spatial prioritization is extremely important to target areas where green roofs may be most effectively implemented. Examining the benefits at an appropriate scale also can help focus green roof policy development and lessen the stormwater impacts from drainage areas that may be particularly detrimental to the receiving water body. Land coverage found in dense urban cores and commercial areas are particularly well suited to extensive green roof systems.

As jurisdictions continue to look for ways to innovatively manage their stormwater, additional tools serve to make this duty easier. In this study, the use of green roofs for stormwater management has been shown to be an effective tool for managing small storms in highly developed areas. Incorporating green roofs into larger watershed management plans will increase flexibility for watershed managers to mitigate environmentally destructive land use practices and provide a new avenue for hydrologic remediation of urban watersheds.

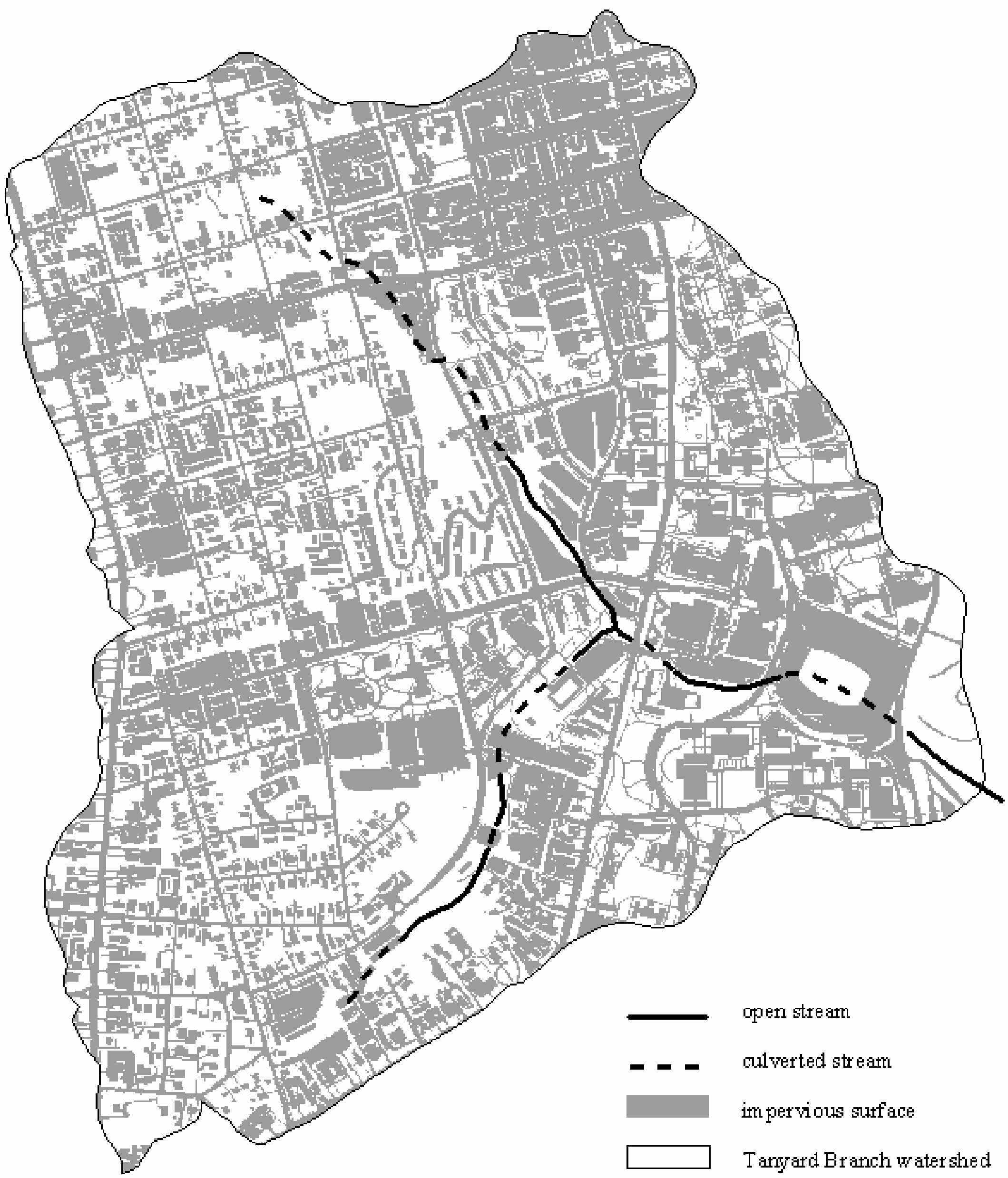


Figure 3.1. Tanyard Branch watershed impervious cover and stream network

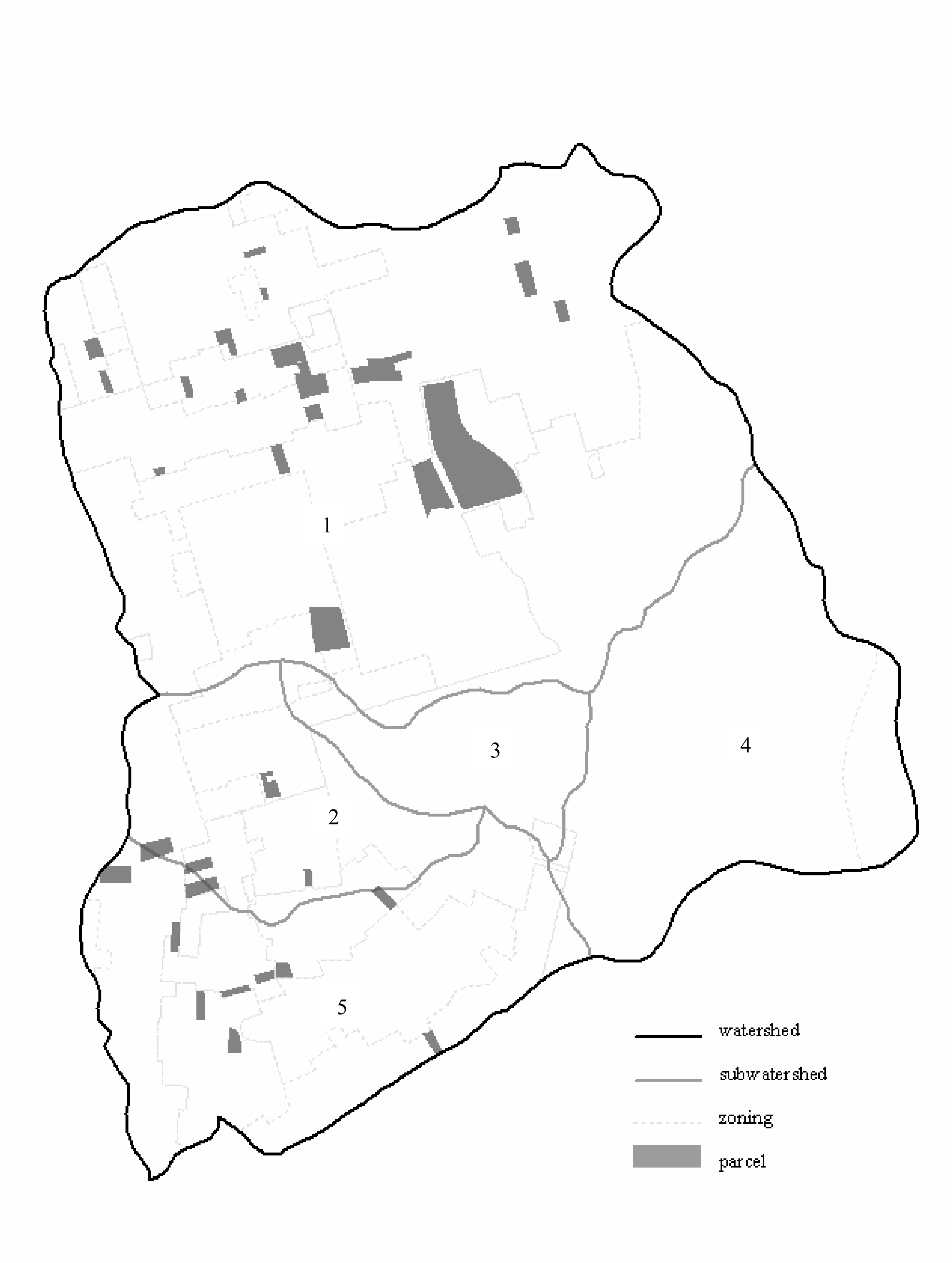


Figure 3.2. Four spatial scales used for CN modeling (subwatersheds are numbered)

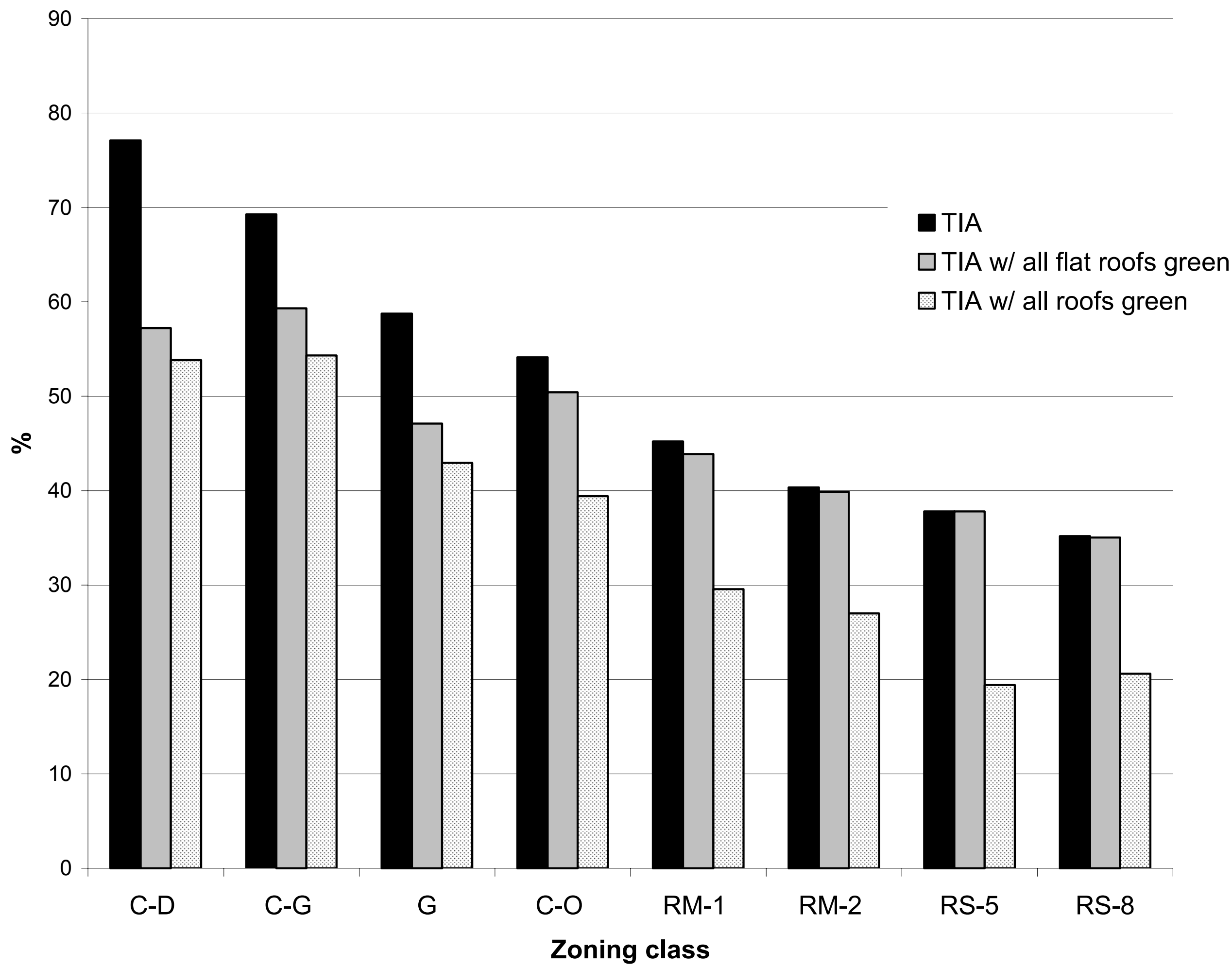


Figure 3.3. Total impervious area (TIA) according to zoning class

Key:
C-D = commercial downtown
C-G = commercial general
G = government
C-O = commercial office
RM-1 = mixed density residential (16 units/.4 ha)
RM-2 = mixed density residential (24 units/.4 ha)
RS-5 = single family residential (6 units/.4 ha)
RS-8 = single family residential (4 units/ .4 ha)

Table 3.1. Runoff volume for existing roofs and all green roof scenarios in hectare-meters from 5 design storms with % change in ( )

		1.27cm		3.05cm		7.92cm		15.85cm		19.51cm	
		existing	all green	existing	all green	existing	all green	existing	all green	existing	all green
Tanyard Branch Watershed		0.481	0.304 (-36.8)	3.194	2.653 (-16.9)	13.421	12.403 (-7.6)	31.590	30.301 (-4.1)	40.126	38.774 (-3.4%)
Subwatershed	1	0..240	0.149 (-37.9)	1.601	1.322 (-17.4)	6.735	6.206 (-7.8)	15.855	15.186 (-4.2)	20.140	19.437 (-3.5)
	2	0.041	0.028 (-31.2)	0.281	0.240 (-14.0)	1.190	1.116 (-6.2)	2.812	2.719 (-3.3)	3.575	3.476 (-2.8)
	3	0.033	0.020 (-36.3)	0.189	0.156 (-17.3)	0.750	0.692 (-7.8)	1.730	1.658 (-4.2)	2.188	2.113 (-3.4)
	4	0.119	0.076 (-36.1)	0.654	0.540 (-17.4)	2.521	2.324 (-7.8)	5.760	5.519 (-4.2)	7.272	7.021 (-3.4)
	5	0.071	0.046 (-35.9)	0.528	0.444 (-15.9)	2.32	2.155 (-7.1)	5.547	5.335 (-3.8)	7.068	6.844 (-3.2)
Zoning	government (university)	0.222	0.144 (-34.6)	1.239	1.025 (-16.6)	4.776	4.420 (-7.4)	10.933	10.498 (-4.0)	13.810	13.357 (-3.3)
	commercial downtown	0.112	0.062 (-45.1)	0.498	0.382 (-23.4)	1.744	1.558 (-10.6)	3.849	3.630 (-5.7)	4.828	4.602 (-4.7)
	commercial general	0.043	0.029 (-32.3)	0.217	0.183 (-15.7)	0.811	0.753 (-7.0)	1.830	1.762 (-3.7)	2.304	2.235 (-3.1)
	commercial office	0.061	0.039 (-34.3)	0.396	0.334 (-15.7)	1.655	1.539 (-7.0)	3.889	3.742 (-3.8)	4.937	4.784 (-3.1)
	mixed density residential (16 units/0.4 ha)	0.053	0.033 (-38.6)	0.417	0.346 (-16.9)	1.873	1.731 (-7.6)	4.509	4.324 (-4.1)	5.753	5.559 (-3.4)
	mixed density residential (24 units/0.4 ha)	0.028	0.017 (-35.4)	0.239	0.204 (-14.7)	1.124	1.050 (-6.5)	2.747	2.651 (-3.5)	3.516	3.414 (-2.9)
	single family residential (6 units/0.4 ha)	0.006	0.003 (-47.0)	0.053	0.042 (-19.9)	0.251	0.228 (-8.9)	0.616	0.586 (-4.9)	0.789	0.757 (-4.0)
	single family residential (4 units/0.4 ha)	0.023	0.013 (-40.0)	0.223	0.187 (-16.2)	1.086	1.008 (-7.2)	2.691	2.586 (-3.9)	3.454	3.342 (-3.2)

Table 3.2. Runoff volume in hectare-meters for existing roofs and flat green roof scenarios from 5 design storms with % change in ( )

		1.27cm		3.05cm		7.92cm		15.85cm		19.51cm	
		existing	all flat green	existing	all flat green	existing	all flat green	existing	all flat green	existing	all flat green
Tanyard Branch Watershed		0.481	0.391 (-18.9)	3.194	2.928 (-8.3)	13.421	12.935 (-3.6)	31.590	30.983 (-1.9)	40.126	39.490 (-1.6)
Subwatershed	1	0..240	0.193 (-19.9)	1.601	1.461 (-8.7)	6.735	6.477 (-3.8)	15.855	15.532 (-2.0)	20.140	19.802 (-1.7)
	2	0.041	0.038 (-7.7)	0.281	0.270 (-3.3)	1.190	1.174 (-1.4)	2.812	2.792 (-0.7)	3.575	3.553 (-0.6)
	3	0.033	0.020 (-36.3)	0.189	0.156 (-17.3)	0.750	0.692 (-7.8)	1.730	1.658 (-4.2)	2.188	2.113 (-3.4)
	4	0.119	0.089 (-24.9)	0.654	0.577 (-11.7)	2.521	2.392 (-5.1)	5.760	5.603 (-2.7)	7.272	7.110 (-2.2)
	5	0.071	0.066 (-8.3)	0.528	0.511 (-3.4)	2.32	2.286 (-1.5)	5.547	5.503 (-0.8)	7.068	7.021 (-0.6)
Zoning	government (university)	0.222	0.162 (-26.6)	1.239	1.075 (-12.5)	4.776	4.511 (-5.5)	10.933	10.611 (-2.9)	13.810	13.477 (-2.4)
	commercial downtown	0.112	0.068 (-39.9)	0.498	0.397 (-20.4)	1.744	1.584 (-9.1)	3.849	3.661 (-4.9)	4.828	4.635 (-4.0)
	commercial general	0.043	0.033 (-22.7)	0.217	0.194 (-10.7)	0.811	0.772 (-4.7)	1.830	1.784 (-2.5)	2.304	2.258 (-2.0)
	commercial office	0.061	0.054 (-9.7)	0.396	0.379 (-4.2)	1.655	1.625 (-1.8)	3.889	3.851 (-0.9)	4.937	4.898 (-0.8)
	mixed density residential (16 units/0.4 ha)	0.053	0.051 (-3.8)	0.417	0.411 (-1.5)	1.873	1.860 (-.65)	4.509	4.493 (-0.3)	5.753	5.737 (-0.3)
	mixed density residential (24 units/0.4 ha)	0.028	0.027 (-1.4)	0.239	0.238 (-0.5)	1.124	1.121 (-0.2)	2.747	2.744 (-0.1)	3.516	3.513 (-0.1)
	single family residential (6 units/0.4 ha)	0.006	0.006 (0.0)	0.053	0.053 (0.0)	0.251	0.251 (0.0)	0.616	0.616 (0.0)	0.789	0.789 (0.0)
	single family residential (4 units/0.4 ha)	0.023	0.023 (0.0)	0.223	0.223 (0.0)	1.086	1.086 (0.0)	2.691	2.691 (-0.0)	3.454	3.454 (0.0)

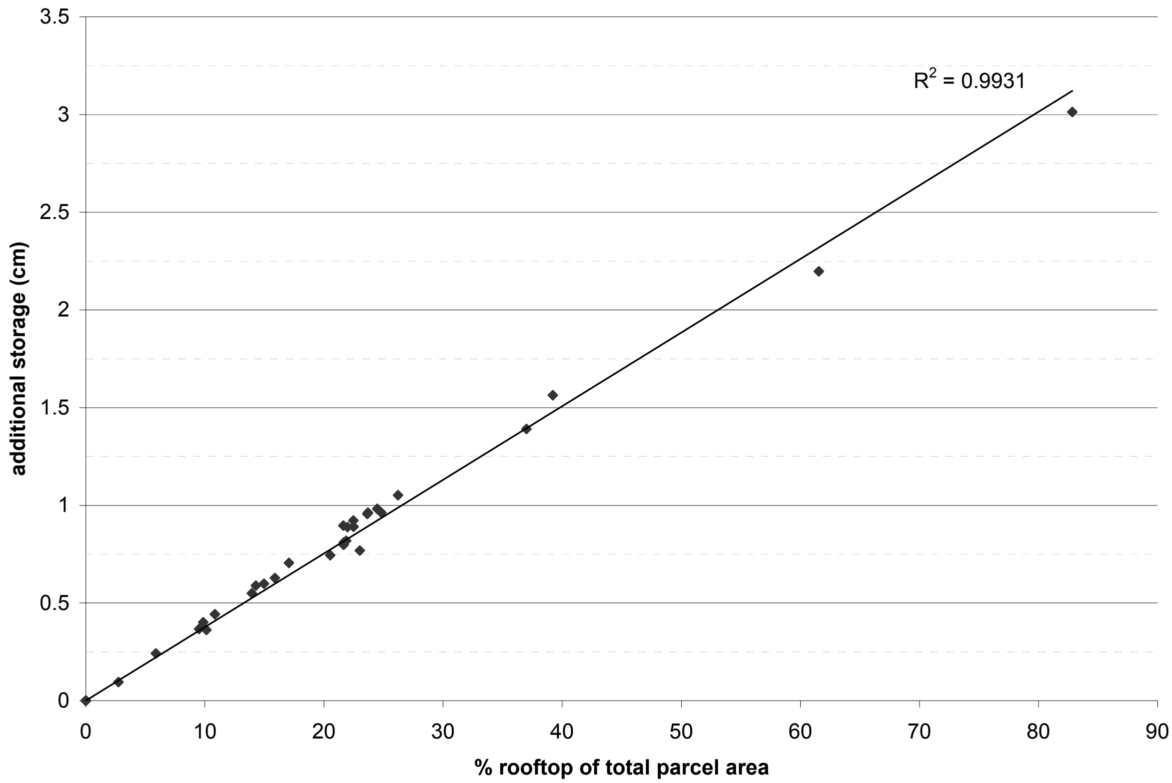


Figure 3.4. Rainfall storage provided by rooftop parcel coverage

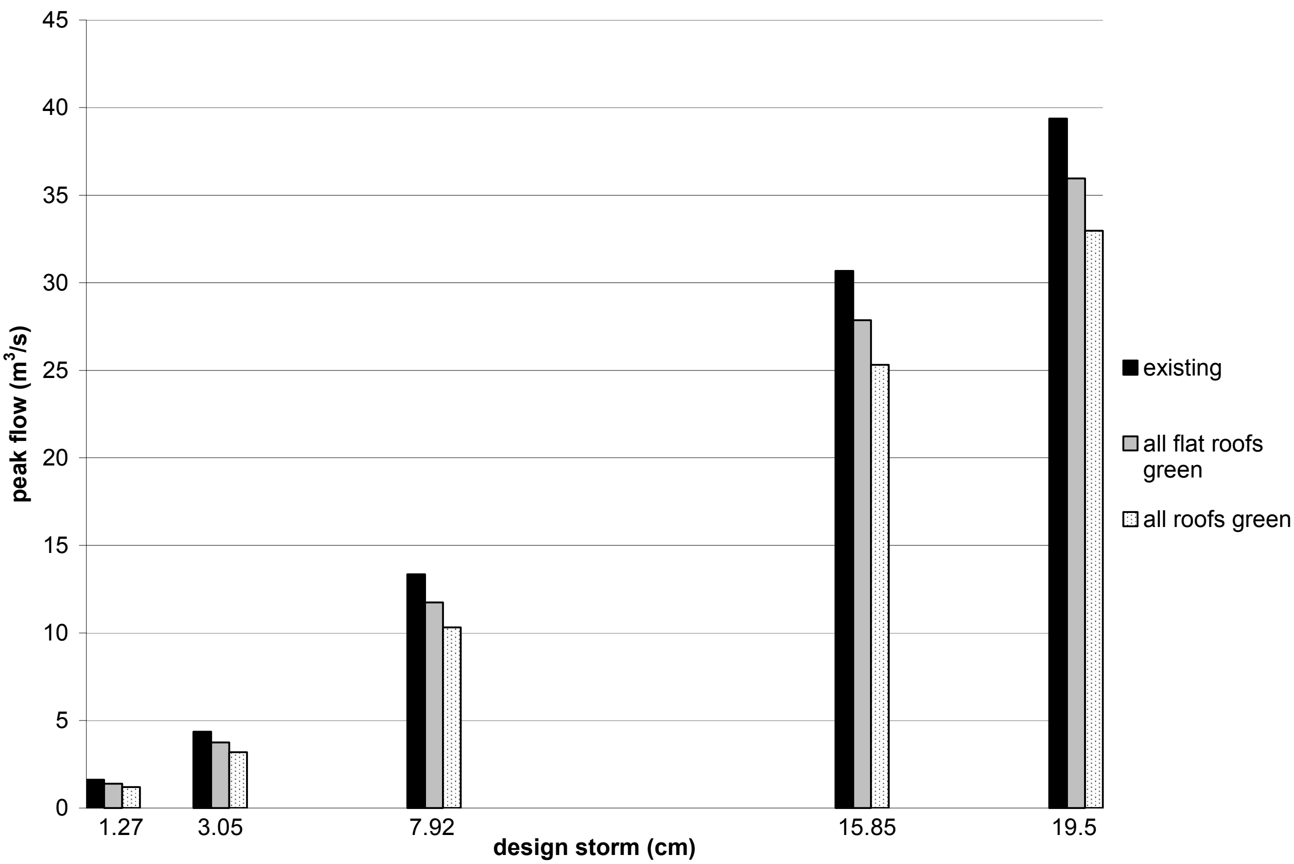


Figure 3.5. Peak flow for five design storms with roof greening scenarios

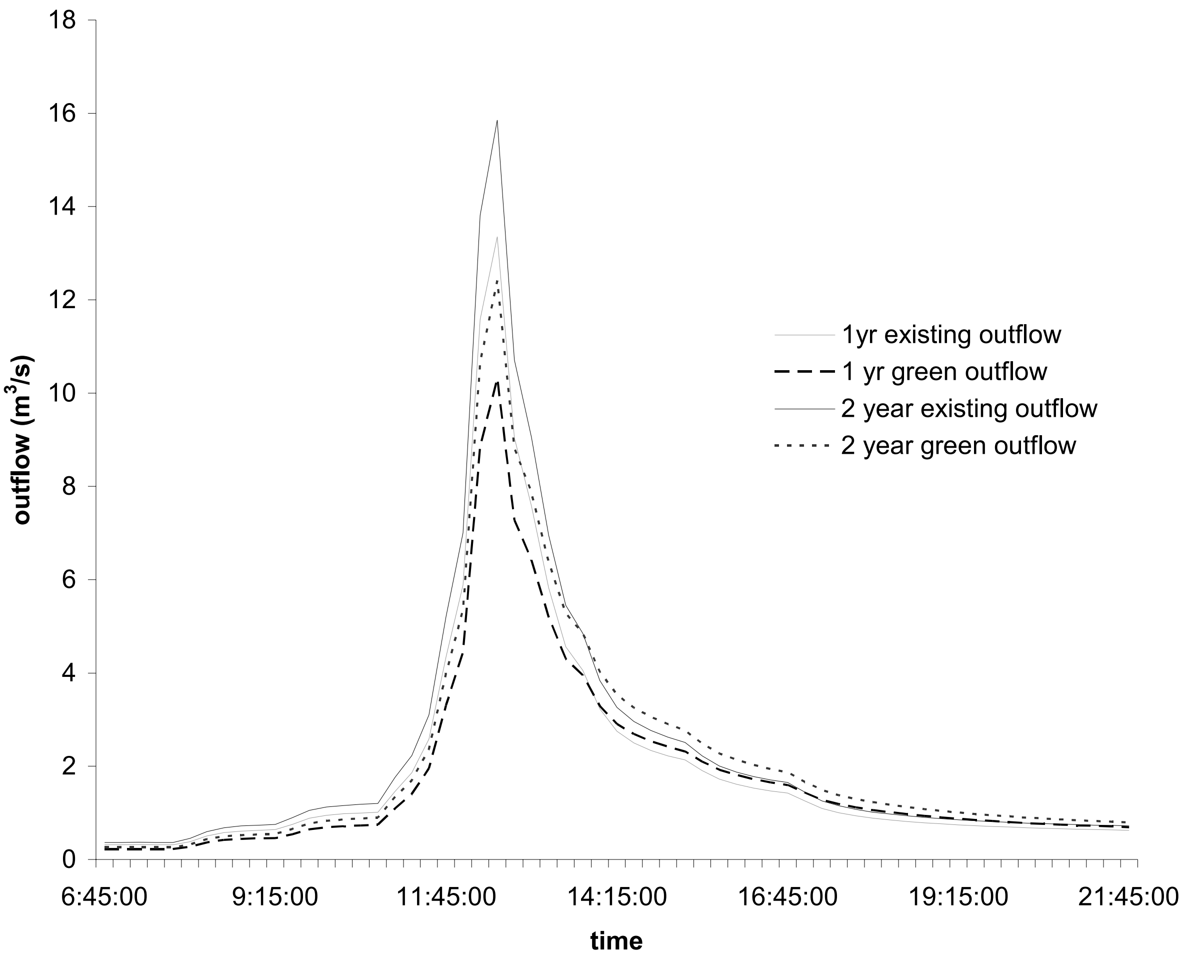


Figure 3.6. Watershed outflow for two small storms under existing and roof greening scenarios

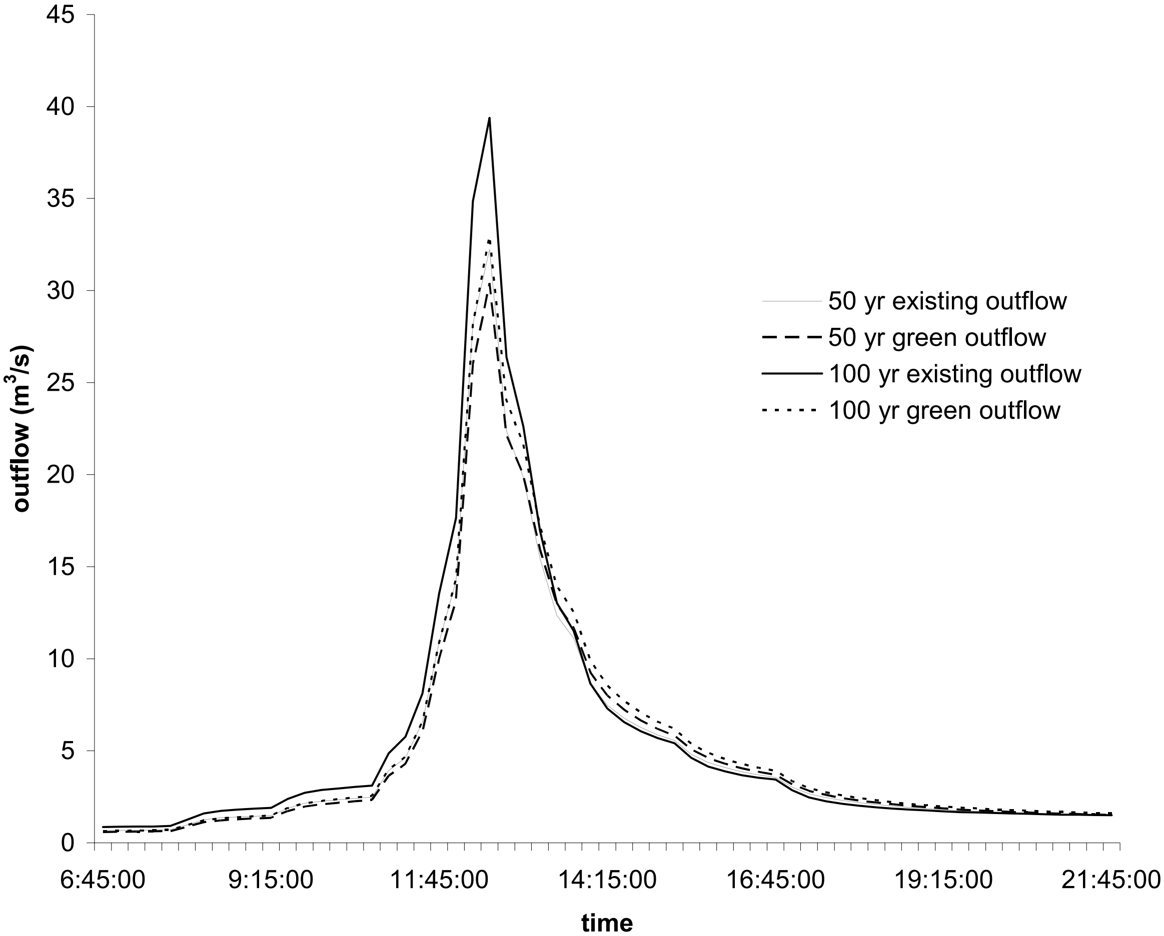


Figure 3.7. Watershed outflow for two large storms under existing and roof greening scenarios

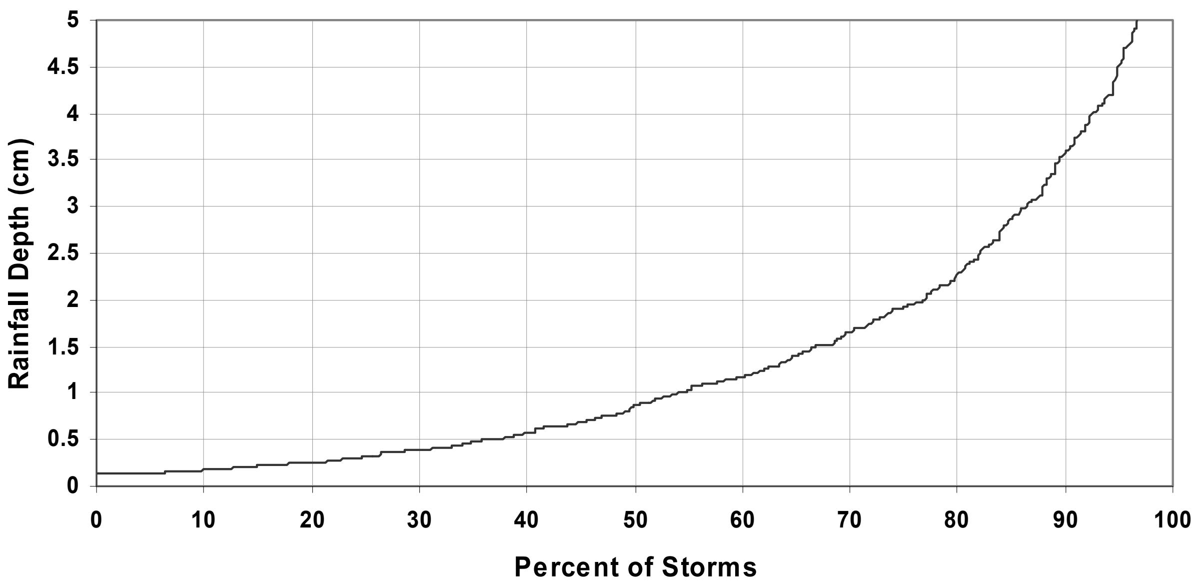


Figure 3.8. Frequency of small storm events for Athens, GA

CHAPTER 4

LIFE CYCLE COST-BENEFIT ANALYSIS OF THIN-LAYER VEGETATED ROOF SYSTEMS[1]

[1] Carter, T.L. and Keeler, A. G. Submitted to *Journal of Environmental Management*, 05/02/06

Abstract

The built environment has been a significant cause of environmental degradation in the previously undeveloped landscape. As public and private interest in restoring the environmental integrity of urban areas continues to increase, new construction practices are being developed that explicitly value beneficial environmental characteristics. The use of vegetation on a rooftop – commonly called a green roof -- as an alternative to traditional roofing materials is an increasingly utilized example of such practices. The vegetation and growing media perform a number of functions that improve environmental performance, including: absorption of rainfall, reduction of roof temperatures, improvement in ambient air quality, and provision of urban habitat. A better accounting of the green roof's total costs and benefits to society and to the private sector will aid in the design of policy instruments and educational materials that affect individual decisions about green roof construction. This study uses data collected from an experimental green roof plot to develop a benefit cost analysis (BCA) for the life cycle of thin-layer green roof systems in an urban watershed. The results from this analysis are compared with a traditional roofing scenario. The net present value (NPV) of this type of green roof currently ranges from 10-14% more expensive than its conventional counterpart. A reduction of 20% in green roof construction cost would make the social NPV of the practice less than traditional roof NPV. Considering the positive social benefits and relatively novel nature of the practice, incentives encouraging the use of this practice in highly urbanized watersheds are strongly recommended.

INDEX WORDS: green roof, green building, cost benefit analysis, best management practices

Introduction

The relationship between the built and natural environment has traditionally been one of complete opposition. Both terrestrial and aquatic ecosystems are drastically, and often times irrevocably, altered during the process of urbanization (Pickett et al, 2001; Paul and Meyer, 2001). Water regulation and supply, erosion control and sediment retention, nutrient cycling, climate regulation, and waste treatment changes are all ecosystem services either eliminated or significantly degraded in highly developed landscapes (Costanza et al, 1997). The construction of man-made structures and impervious surfaces that are a defining feature of highly developed areas are an important causal element behind environmental decline in urban areas (Arnold and Gibbons, 1996).

One reason why construction practices lead to environmental problems is that the costs of environmental degradation are not fully realized by the party who caused the damage. Thus, when evaluating construction costs, developers have historically viewed environmental damage as exogenous to the development process. Federal and state environmental laws have altered this situation to some extent in the last several decades. Developers have been limited by laws and regulations concerning erosion and sedimentation control, post-construction stormwater control and urban tree preservation. Nonetheless, developers still make land use decisions without considering the full cost of the environmental damage that their activities create.

Positive incentives have been developed for more ecologically sensitive development, particularly for buildings. A rating system called Leadership in Energy and Environmental Design (LEED) has been created by the United States Green Building Council for certification of commercial buildings that have a reduced environmental impact. As of 2005, 393 projects had received LEED certification and many municipalities require buildings built with public funds to receive LEED certification (Cassidy, 2003). Other organizations such as the National Association of Home Builders have recently developed green building guidelines based on similar standards (NAHB, 2004).

Specific building construction practices are being refined to create structures which have a much smaller impact on the surrounding landscape than previously thought possible. At the broadest scale, sites are selected for their proximity to public transportation, their ability to maximize open space and protect habitat, effectively manage stormwater runoff, address the heat island effect found in urban areas, and reduce light pollution (www.usgbc.org). Sustainable water use for a building may involve xeriscaping, greywater reuse for irrigation, and the use of low-flow or composting toilets and non-water urinals which are becoming increasingly cost effective (Gleick, 2003). A building's energy use is also an extremely important component of sustainable design. From simply designing smaller structures to installing active solar panels or other on-site sources of self-supplied energy, there are a wide range of practices available to reduce a building's reliance upon fossil fuel energy sources. Increasingly, building materials contain recycled material content in new construction and attempt to reuse as much of the existing structure in renovations as possible (Horvath, 2004). Indoor environmental quality is also an important feature of green buildings. Paints and adhesives designated "Low-VOC" or "No VOC" (volatile organic compounds) reduces the low level toxic emissions found in older materials and improves indoor air quality for building occupants. Day-lighting larger portions of the structure improve the working environment in commercial buildings as well as reducing energy costs when high performance windows are used.

Of these many ways that buildings can be designed and constructed in a more sustainable manner, the roof surface can easily be overlooked as space that can be designed into an environmental amenity for the building, not simply contributing to environmental problems. The rooftop is typically the same size as the building's footprint and is the structure's prime barrier against precipitation and solar radiation. To the extent that the roof surface can be transformed into useful space, the building becomes economically and functionally more efficient and can have a more benign effect on the surrounding landscape.

Published research has focused largely on the energy savings associated with different types of roofing systems. Akbari et al (1997) found that changing a roof from one with low albedo to high albedo in Sacramento, CA would decrease cooling energy use by 80%. Other studies have documented the affect of insulation on the heat flux at the roof surface (Al-Sanea, 2002), how to incorporate active and passive solar designs into rooftop systems (Heras et al, 2005; Maneewan et al, 2005), and the energy benefits associated with ventilated roof systems (Ciampi et al, 2005). These alternatives to traditional roofing systems are beginning to gain more of a market share and EPA has established an Energy Star rating system for roofing products, primarily identifying roofing membranes which have high albedos and the potential to significantly reduce building energy costs (www.energystar.gov).

While energy savings are an important function of alternative roof systems, other benefits may also be realized. In a traditional roofing system, rainfall hits the rooftop and is quickly channeled into the nearest gutter or storm sewer system with the goal being to have the roof shed water as quickly as possible. As regulations have mandated stormwater management plans for municipalities, rooftop runoff control has become an important management practice for minimizing degradation of aquatic ecosystems. One solution is to create rainwater storage tanks which can capture rainfall from the roof surface and store it for a time before it is reused or slowly discharged (Vaes and Berlamont, 2001)

The application of vegetation and growing media to the roof surface is an increasingly popular practice which produces improvements in both energy conservation and stormwater management. These green roofs are multi-functional in that they provide numerous environmental benefits simultaneously. These benefits include: decreasing the surface temperature of the roof membrane and energy use in the building (Kumar and Kaushik, 2005), retaining stormwater for small storm events (Carter and Rasmussen, in press), increasing biodiversity and habitat in urban areas largely devoid of such space (Kim, 2004; Brenneisen, 2005), and improving ambient air quality (Clark et al, 2005). While these benefits are inherent in all green roof systems to some degree, depending on the design of the roof there is potential for other amenities as well. Accessibility and aesthetic appeal for the building occupants, sound insulation and the potential for urban agriculture are all realistic benefits provided by green roof applications (Peck et al, 1999).

While green roof projects have recently generated significant interest in design fields such as landscape architecture, little research has been done to evaluate the costs and benefits of green roof systems for urban applications. Published reports typically focus on a single green roof benefit (Wong et al, 2003) or qualitatively describe a series of benefits derived from different types of green roofs (Peck et al, 1999). This lack of focused quantification can potentially lead to unrealistic or inappropriate policy recommendations.

This study quantifies the costs and benefits of thin-layer, or extensive, green roof systems as they compare to typical flat roofs in an urban watershed. The authors combine local construction costs for an established green roof test site with experimentally collected stormwater retention data and building energy analysis data into a single metric using conventional cost-benefit analytical techniques applied over the life-cycle of a typical green roof.

A local watershed is evaluated using a variety of spatial scales as a case study for application of widespread green roofs. As green roof popularity continues to grow, it is important for accurate life cycle benefit-cost analyses (BCA) of green roof systems to be performed to inform both policy makers who may allocate public funds for projects with public benefits, and private building owners who may see a future financial incentive to invest in new and relatively unproven technology.

Materials and Methods

BCA framework

Green roof BCA was performed according to an 8-stage framework found in Hanley and Spash (1993). The stages are: definition of project, identification of project impacts, identification of which impacts are economically relevant, physical quantification of relevant impacts, discounting of cost and benefit flows, application the net present value test, and sensitivity analysis.

Project site and test plot

The project examines the feasibility of replacing all the flat roofs in an urban watershed with green roof systems. The Tanyard Branch watershed was selected as a study site. This highly urbanized watershed contains a second order stream system and is located in Athens, GA approximately 60 miles east of Atlanta, GA. The watershed contains significant portions of the downtown commercial district of Athens, the University of Georgia, and both single and multi-family residential areas. Using 2003 aerial photography, the impervious surfaces including rooftops were digitized into a geographic information system (GIS). 53.8% of the land cover is impervious surface with rooftops accounting for 15.9% of the total land cover in the watershed (Figure 4.1). The Tanyard Branch creek is listed as not meeting its designated use due to elevated fecal coliform counts with the cumulative effects of urbanization in the watershed cited as the cause of this degradation (Herbert, 2003). Flat roofs are the most viable candidates for greening as they often require no additional structural support and minimal design expertise for green roof installation (Banting, 2005). Flat roofs constitute 176,234 m^2 or 7.4% of impervious surface in the watershed (Figure 4.2).

A 42.64 m^2 green roof test plot was established in October, 2002 on the campus of the University of Georgia (Figure 4.3). The test plot was designed to be simple to build and easy to replicate using American Hydrotech's extensive garden roof. American Hydrotech, Inc is a single source supplier for the specialized green roofing materials. These materials included a WSF40 root protection sheet, a SSM 45 moisture retention mat, a Floradrain FD40 synthetic drainage panel, and a Systemfilter SF geotextile filter sheet (American Hydrotech, 2002). The growing media was a Lightweight Roof Garden mix provided by ItSaul Natural, LLC. This soil mix is a blend of 55% Stalite expanded slate, 30% USGA sand, and 15% organic matter composed primarily of worm castings. This mix was spread to a depth of 7.62 cm. Six drought-tolerant plant species were selected for their ability to survive low nutrient conditions and extreme temperature fluctuations found at the roof surface. No irrigation or fertilization was applied except for the initial three days of planting.

Theory and calculation

The economically relevant impacts of widespread roof greening were established and physical quantification of these impacts were performed using the green roof test plot as a template for all new green roofs in the watershed. The benefits were divided into categories found in Table 4.1 with the conceptual framework outlined in Figure 4.4. Analysis for the social BCA was performed at the watershed scale while a private BCA was performed using a typical one-story 929 m^2 roof. Details of each category follow below and the results are summarized in Table 4.2. All dollar amounts have been converted to 2005 dollars using the Consumer Price Index.

Construction and maintenance

The first category deals with construction and maintenance expenses. The construction costs of a typical built-up bituminous roof system on a concrete roof deck were taken from personal interviews with three local roofing contractors and additional verification from the Means construction cost data (2005). The traditional roof was assumed to have a 20 year guarantee on the waterproofing membrane and thus an effective twenty-year life before replacement. The construction costs of a conventional roof were estimated to be $83.78/$m^2$.

The cost estimate on the green roof was obtained from the test site as well as personal interviews with three single source green roofing manufacturers. The average cost from these sources was compiled into a unit cost estimate of for initial construction of an extensive (7.62 cm of growing media) roof system. No additional waterproofing cost was added. While each installation would not have identical costs depending on accessibility, structural integrity, and design considerations, an estimate of $158.82/$m^2$ was used based on average costs from the manufacturers and the local test plot (Table 4.3). Maintenance on a thin-layer green roof is considered equivalent to the maintenance schedule of a traditional roof with visual inspections twice per year. Many industry groups claim green roofs can extend the life of the waterproofing membrane over 200%. This is due to the vegetation and growing media protecting the membrane from harmful ultra-violet radiation and physical damage. Since green roofs have only been used extensively in the United States in the past decade and there are few examples to verify this claim. However, engineered green roofs in Europe have been shown to function for over twice the life span of conventional roofing systems (Kohler et al., 2001). For this study, green roofs are assumed to last for forty years – twice the life span of conventional roofs.

While the unit construction cost of \$158.82 /m^2 is used for our base case analysis, this most likely is at the high end of what would be experienced for widespread green roof construction in the Tanyard watershed. It is partially based on estimates of what would be required to build an initial demonstration roof, and thus ignores economies of scale in materials purchasing as well as innovations in construction techniques developed as local contractors gained experience. Second, in Germany where the industry has been established for over 30 years, construction costs may be as much as 50% lower for larger installations (www.greenroofs.com). It is therefore assumed that true construction costs will vary between 50% and 100% of this initial estimate when the sensitivity analysis is performed.

Stormwater management

Stormwater management is a second economically relevant category. Under the U.S. Environmental Protection Agency's National Pollutant Discharge Elimination System (NPDES) Phase I and II stormwater rules, jurisdictions with municipal separate storm sewer systems (MS4s) are required to develop a stormwater management program relying upon stormwater best management practices (BMPs) to control stormwater discharges. Green roofs may potentially be one of the BMPs used to accomplish the goals of this program. Green roofs have been shown to retain a significantly higher percentage of stormwater when compared to a traditional roofing system. A recent study in Michigan documented how, during medium volume rain events, a thin-layer green roof system retained 48% more rainfall than a gravel ballast roof (VanWoert et al, 2005). The local test roof was monitored for its ability to retain stormwater from November 2003 – November 2004. The green roof retained, on average, more than 77% of the rainfall throughout the year with retention performance determined primarily by total storm rainfall volume. Details from this study can be found in Carter and Rasmussen (in press).

Using the stormwater retention performance data and watershed spatial information, total additional stormwater storage from greening all flat roofs could be estimated for Tanyard Branch. The spatial analysis was done using ArcView 3.2, a commonly used geographic information system (GIS) software package (ESRI, 1999). 2003 full color aerial photographs with 0.15 m pixel resolution were obtained from the city of Athens. From these photographs, flat roofs in the watershed were digitized at a scale of 1:500 (Figure 4.2). Ground-truthing was also performed. Extensive greening provided an additional 4.27 cm of stormwater storage depth which results in total storage for the watershed of 7542 m^3. This retention data then compared with published retention and cost data from other stormwater BMPs for determining the cost for an equal amount of storage using other practices given the land cover in the watershed (EPA, 1999). Since the watershed is already highly urbanized, only BMPs which are typically used in an ultra-urban application were considered. These BMPs include sand filters, bioretention areas, and porous pavement. Depending on the type of BMP used in the comparison, different cost savings may be realized (Table 4.4). The avoided cost of using alternative stormwater BMPs is considered part of compliance with Phase II stormwater rules in Athens and the benefits are included in the social BCA. Analysis was run by dividing the total stormwater storage volume provided by green roofs equally among the three alternative BMPs and calculating the total cost of this alternative scenario (Table 4.4).

An additional private stormwater benefit for green roofs may be realized in the regulatory arena. Increasingly, jurisdictions are creating stormwater utilities which are charge fees to parcel owners based on their parcel’s stormwater contribution to the system. These utilities generate income used exclusively for stormwater management operations. Parcel owners are commonly given exemptions or credits if they can demonstrate that they are keeping their site from contributing runoff to the stormwater system. Athens has enacted a stormwater utility and incorporated a system of credits for demonstrated on-site management. With the proper documentation, green roofs are assumed to accomplish the water quantity standards required for the stormwater credit. In the case of the roofs in Tanyard Branch, this results in a savings ranging from \$0.04/m^2 to \$0.08/sm depending on building type (Table 4.5). Calculations were performed based on the spatial information of the buildings in the watershed. The majority of the savings came from commercial, government, and multi-family buildings with the average unit cost being \$0.04/m^2. The total value was applied to the private BCA. This is a transfer payment which does not increase social welfare and therefore is not included in the social BCA.

Another aspect of stormwater management is the drainage collection of pipes, inlets and junction boxes collectively termed the storm sewer system. Retention of stormwater before it reaches the system may result in resizing of the pipes during maintenance and repair of the infrastructure. Athens contains an MS4 and spatial data for the storm sewer system was acquired for the watershed from the city of Athens and the University of Georgia. Stormwater pipes in Athens-Clarke County are a minimum of 38.1cm (15 in) and most are designed for the 25-year storm event, which in Athens is 15.85 cm. Pipe costs were estimated according to Means (2005) with unlisted pipe dimensions priced using the power function derived from Means (2005):

$$C=0.6318D^{1.4086}$$

where:

C= cost of pipe (\$/lf)

D= diameter of the pipe (in)

Reductions in the storm flow volumes from the watershed outfall were calculated for a variety of storm events using StormNet Builder, a comprehensive stormwater modeling package (Boss International, 2005). This study is detailed in Carter (2006). The cost savings from a reduction in pipe size was then calculated and converted to a cost per linear meter of pipe. This cost saving showed a 4.6% reduction in size for the 25 year event and a 4.4% reduction for the 100 year event. These reductions are not significant enough to result in changes in pipe sizing due to green roof implementation; therefore no economic benefit from pipe resizing was used in the analysis.

Other relevant features of stormwater management affected by widespread green roof implementation were determined not to be applicable to this particular watershed. Included in this is the effect of green roof stormwater retention on the reduction of combined sewer overflows (CSOs), a phenomenon having large environmental impacts resulting from the stormwater systems found in many larger cities. It was estimated in the city of Toronto, for example, that avoiding CSOs using green roofs would save the city $46.6 million in infrastructure savings (Banting et al, 2005). Athens, however, has separate sewer systems for stormwater and waste water and therefore this analysis could not be performed. Also, a reduction in nuisance flooding, which is a commonly quantified through flood insurance premiums, is not appropriate for this stream system as the stream is piped or highly incised with no flood risks in the residential sections of the watershed.

Energy and insulation

The third economically relevant category is energy and insulation. Green roofs act to reduce the rooftop surface temperatures through leaf shading direct solar radiation, evaporation of moisture at the surface and transpiration of the plants which cool the ambient air above the roof. Thin-layer green roof systems have consistently been shown to reduce the temperature fluctuations at the roof surface (Onmura et al., 2001). Whether this translates into significant energy savings is not clear from the literature as in one study, energy use was evaluated for small experimental sheds containing green roofs and the vegetated treatments had little effect on total energy use in each structure (DeNardo et al, 2003). Other research, however, suggests that considerable energy cost savings can be realized when green roofs are used; enough for the life cycle cost of a green roof to be less than a traditional roof when energy savings were included in the analysis (Wong et al 2003).

For the energy related benefits in this study, local data were used. Adjacent to the stormwater green roof test plot, a second experimental roof was constructed and an analysis of the thermal conductivity of growing media as well as energy load modeling was performed. Details from this study can be found in Hilten (2005). Cost savings from the additional insulation provided by the green roof as well as the reductions in the heating and cooling loads were found for the building and converted into unit savings to be applied across the watershed. The green roof's insulating value was equivalent to R-2.8 which is similar to 2.54 cm of fiberboard, fiberglass, or perlite. These types of insulation average to \$3.98/m^2 and this value may be considered an avoided cost in the green roofing analysis. If this avoided cost is used, however, the building owner will not realize any energy savings as there is no net increase in insulation.

A more likely scenario is that the green roof will be added and provide additional insulation, not used as replacement for traditional insulation. This additional insulation value creates energy savings for the building owner. Using test plot data, energy load modeling was performed on a model 929 m^2 building (Hilten, 2005). The energy load reduction from the green roof system was modeled at 4222.56 kwh/yr. This is an energy savings of 3.3% which is less than half of the 8% used in the Wong et al (2003) study. Residential rate surveys for the 2005 year were acquired from the Georgia Public Service Commission and the 2005 average rate of \$0.082/kwh was applied to the energy savings modeled in the building. This current price is used for the conservative base case BCA, but we believe that assuming electricity prices will remain constant in real terms over the next forty years is extremely optimistic. Policies to limit air pollution and climate change are likely to bring about significant increases in this price. For the sensitivity analysis, it is assumed that the actual rate of increase in energy prices will vary on a uniform distribution between 0% (the base case assumption) and 8% (a pessimistic but plausible assumption under significant future environmental regulation).All buildings in the watershed were estimated to have the same energy savings, although savings may vary based on the number of stories and orientation of each structure. The unit energy savings for current energy rates was \$0.37/m^2 (Table 4.6).

Air quality

A fourth economically relevant category is air quality. While the potential may be great for green roofs to improve air quality in densely developed areas, the type of vegetation found on the rooftop largely determines the amount of air quality improvement. Trees, grasses, and shrubs both filter pollutants and transpire moisture much differently than the Sedum plant species commonly found on modern green roof applications. Cross-applying air quality improvements from one type of green roof application to another can be very misleading. For example, air quality benefits have been modeled for grass roofs in Toronto with the authors finding significant economic benefits to air quality under grass roofing scenarios (Currie and Bass, 2005). The Georgia test plot, however, was designed to be simple and easily replicable using Sedum plants. These plants do not have the same leaf area index, photosynthetic activity, or growth pattern as grasses thus making this particular air quality benefit unsuitable for this study.

Other researchers have modeled air quality improvements through nitrogen oxide uptake made by the *Crassulaceae* plant family of which Sedum is a member. Economic quantification of these improvements was then possible by including Sedum green roofs as part of a cap-and-trade emissions credit system. Using 2005 market value for NOx emission credits of $3375/ton, Clark et al (2005) estimated the credit for a Sedum green roof to be $\$0.11/m^2$. This value was applied to the current analysis as the air quality benefit since it was deemed more appropriate for the roof system used in this study. Both the private and public sectors benefit from this technology as green roofs reduce the pollutant loads in the ambient air of the city improving social welfare while allowing the private building owner to receive economic compensation from providing a service for industries looking to offset their polluting activities.

Unquantifiable categories

Other categories may be economically relevant in particular green roof applications, but were not included in this analysis either because of a lack of reliable data or incompatibility of the benefit with the type of green roof used in this study. Urban green space and habitat is clearly a benefit provided by green roofs and rooftop greening has been incorporated into plans to maintain urban habitat networks (Kim, 2004). Valuation of urban greenspace is typically done through hedonic analysis relating house prices to greenspace type and location (Morancho, 2003). While accessible rooftops provide the building owner or tenant with additional space for recreation or growing vegetables, the roof designed in this study does not perform these functions. The greenspace value must be derived strictly by the habitat value for biotic communities on the roofs themselves which is difficult to quantify and outside the scope of this project.

Urban centers have air temperatures higher than surrounding rural areas, a phenomenon commonly known as the urban heat island. In theory, since green roofs reduce the surface temperature of the rooftop, the ambient air temperature is lowered thus reducing the heat flow into the building and concomitant energy use needed to maintain comfortable interior building temperatures. Energy models demonstrate that widespread roof greening could lower temperatures city-wide by 0.1 - 0.8 degrees Celsius, a negligible amount considering the uncertainty in the models (Bass et al, 2003). Until more robust studies demonstrate otherwise, the energy cost savings from reducing the urban heat island due to widespread roof greening will be considered speculative and not included in this analysis.

Results

Discounting of benefit and cost flows and sensitivity analysis

The period of analysis was one green roofing cycle which was estimated to be 40 years based on the doubling of the roof life due to the vegetated cover. Private BCA for greening a single flat roof of 929 m^2 as well as a social BCA of greening all the flat roofs in the watershed was performed. All roof greening occurred at year zero. Traditional roofs were greened at year zero and also underwent one reroofing cycle at year 20. Avoided stormwater costs were applied at year zero. Energy and air quality benefits were applied every year of the analysis. A discount rate of 4% was applied to the reroofing scenario as well as all the green roof benefits. Green roof benefit results from these runs are shown in Tables 4.7 and 4.8. These are considered conservative benefit estimates where current pricing conditions are assumed and values based on the campus test plot are used.

Applying the NPV test

Compiling all the discounted costs and benefits associated with these two roofing systems allows for a NPV test to be performed. Using a 4% discount rate over 40 years, the total costs of installing thin-layer green roof systems on the flat roofs in the Tanyard Branch watershed are $27,451,153. The total costs of traditional built-up roofing systems the over this same time period is $21,552,206. If an equal distribution of all three stormwater BMPs across the watershed is assumed, social benefits equal $3,283,488.37 and a social NPV of $24,167,665 which is 12.14% more than traditional roofing (Table 4.9).

The private analysis performed on an individual roof shows NPV of green roofs to be relatively more costly for the building owner when compared with the social BCA. Private costs differ in that they include a stormwater utility fee credit rather than avoided stormwater BMP costs. This results in a total construction cost of $144,478 for green roofs and 113,353 for conventional roofs at a 4% discount rate on a 929 m^2 building. Total private benefits from green roofing for the private building totaled $9,634. This is 18.87% more than typical roofing.

Sensitivity analysis

The NPV test was recalculated with changes to various key parameters for sensitivity analysis. Sensitivity analysis helps determine on which parameters the NPV outcomes depend the most (Hanley and Spash, 1993). The parameters were allowed to vary randomly between ranges of expected values over 10,000 trials. An average value from these trials was then calculated and compared with values found for the green roof NPV base case (Figure 4.5). Sensitivity analysis was run for both the private and public green roofing scenarios.

The first parameter was the discount rate. Discount rates were modeled around the initial 4%, between the rates of 2% and 6%. Another key parameter was roof construction costs. As the industry continues to mature in North America it is likely that initial construction costs will decrease. Analysis was run with the cost of the green roofing system ranging from the existing cost to a 50% reduction in green roof construction costs. Finally, volatility in energy prices was considered with energy prices ranging from existing prices to a yearly increase of 8%.

Our sensitivity analysis is asymmetric, that is while discount rates vary around the central estimate, both green roof construction costs and energy costs vary only in the direction that is more sympathetic to the economics of using green roofs relative to conventional roofs. This is done because the current point estimates are in fact at the extremes. Green roofs are not going to be more expensive than our demonstration roof under conditions of dramatically increased construction, and electricity prices are not going to be lower than current prices given the expected course of environmental regulation and energy supply and demand. The assumptions used in this sensitivity analysis give a better picture of what the real economics of green roof construction are likely to be, while the base case estimate is a conservative or almost-worst-case scenario.

The results from the sensitivity analysis demonstrated that given realistic assumptions about the changes in the costs and benefits of implementing green roof systems, the average NPV of green roofs is less than the current NPV of black roofs meaning that over the roof's life cycle it is cheaper to install green roofs than their traditional counterpart. The most important parameter was the construction cost estimate which averaged \$116.76 / m^2, down from \$155.41/m^2. Change in green roof benefits due to increased energy prices translated into significantly more energy benefits over the life cycle of the roof, up to \$17.46/m^2 from \$7.32/m^2.

In total, the average social benefit from using green roofs totaled $34.95/m^2$ and the average green roof private benefit was $26.70/m^2$ using the mean values created by the sensitivity analysis (Figure 4.5). Comparing the cost ratio between green and traditional roofing for the conservative NPV estimate and the average estimate generated by the sensitivity analysis show green roofs drop $0.40 on every dollar down to $0.79 from $1.19 for the private scenario and down to $0.72 from $1.12 when social accounting is performed (Table 4.9).

Discussion

BCA of widespread extensive roof greening in the Tanyard Branch watershed reveals a number of important considerations for both the private and public sectors when considering green roof installation. The most significant economic benefits are the increase in roof life, stormwater BMP cost avoidance, and energy savings. The main construction benefit, and best overall benefit in economic terms, of the extensive green roof is that it extends the life of the waterproofing membrane and eliminates the need for frequent reroofing. Without this benefit, green roofs would cost over 85% more than their traditional counterpart. One problem in realizing this benefit is that many waterproofing companies will still only guarantee their premium membranes for 25 years, which may reduce the incentive for a building owner to invest in a green roof during initial construction. As long-term green roof projects are built and monitored, more experience and ultimately green roof life warrantees may help institutionalize this benefit.

Avoiding the cost of other more expensive stormwater BMPs is an important green roof benefit. Since green roofs do not consume valuable urban land, there is no opportunity cost associated with them as there may be with other stormwater BMPs such as bioretention areas. Additionally, green roofs are independent of watershed soil type. They can be implemented anywhere there is a building as opposed to porous pavements, for example, which must have adequate soil permeability before installation is possible (Ferguson, 2005). This analysis demonstrates that green roofs are most practically implemented in densely developed urban centers where other practices are impossible or cost-prohibitive. This stormwater benefit is also public, accomplishing water quality and quantity goals for the jurisdiction, and therefore justifies the use of public funds to encourage private building owners to use green roofs for stormwater mitigation.

Annual energy savings for building owners total over $65,000 in the watershed. While not as significant as extended roof life, this private benefit will be continuously realized each year and help offset some of the initial upfront cost for the building owner. If the building is rented, as many commercial structures are, the tenant will receive this savings. This benefit may function as a marketing tool for the building owner to attract new tenants when leases are renewed. Given uncertainties about energy prices due to the possibility of increased regulation due to air quality and climate change concerns, it is possible that the conservative case has significantly underestimated these benefits. Sensitivity analysis shows that increasing energy prices would result in over $3,000,000 savings over the life cycle of the roof.

The benefit to the existing storm sewer system in the Tanyard Branch watershed is relatively small in economic terms. This is primarily due to the nature of the stream system and the type of sewerage found in the watershed. The highly impacted urban stream shows little potential for economically quantifiable improvement strictly with green roof implementation. Much of the stream is piped and culverted with no change in the sizing of these facilities when green roofs are implemented. This is because extensive green roofs are highly effective at retaining stormwater for small storm events with recurrence intervals of 1-2 years, but are less effective at retaining significant portions of runoff from the larger 25-100 year storms. Stormwater systems are typically designed for these larger storm flows.

Additionally, the flood mitigation benefit is minimal. The geomorphology of Tanyard Branch creek has been dramatically altered by urbanization to the point where the incised banks will only flood on a recurrence interval of a few billion years or effectively never for the purposes of this study (Herbert et al, 2003). There may potentially be marginal improvement in the stream ecosystem with reduction of sediment transport capacity and reduced volume and frequency of runoff from small storm events. Contingent valuation studies or hedonic property valuation of these improvements are difficult as the majority of the day-lit stream reaches are on a single parcel of the campus of the University of Georgia. These site-specific conditions are important qualifiers that may not be true when evaluating green roof benefits in other watersheds.

Sensitivity analysis demonstrates that application of green roofs under varying market conditions can significantly influence whether or not green roofs pass the NPV test when compared to traditional roofs. The base green roofing case used in this analysis is more of a "worst case scenario" than a realistic picture of future green roof installations. The average costs represented in the sensitivity analysis may be a more realistic picture of the pricing that future green roof installers will face. Since construction costs are the most likely of the parameters to decrease as well as the most influential in the NPV performed in this analysis, the conditions appear favorable for thin layer green roof systems to become more profitable than built-up asphalt roofs with further cost reductions among firms in the industry. Direct production and specialization in Germany has led to low unit costs of green roofing materials relative to the United States. A reason for this is that many of the single-source green roof suppliers in the

United States simply are dealers of green roof products imported from German green roof companies, which increases the total cost of these materials. Further maturation of the industry in the United States should expand opportunities for more efficiency and price reductions across the spectrum of green roof products and services.

Conclusions

Expansion of urban areas and the built environment, combined with greater public interest in maintaining the integrity of ecological systems in these areas, has caused the construction industry to begin developing practices that have less environmental impact. Innovative new materials and techniques will be largely governed by economic returns on this investment. Since many of the environmental goods affected by development are public in nature and rarely internalized by private firms, it is important to comprehensively evaluate each new practice so that there is a clear accounting of the costs and benefits to society as well as to private building owners.

This study evaluated one such innovative practice: the extensive green roof system. Applying a life cycle BCA to this practice demonstrates that under current conditions, the NPV of traditional roofs is substantially less than the when green roofs are built in the Tanyard Branch watershed. This may not be surprising, however, due to the novelty of the technology and the unique conditions in the Tanyard Branch watershed which are not ideal for realizing all green roof benefits. Changing reasonable assumptions about this analysis shows that green roofs may be more cost effective than traditional roofs given changes in green roof construction costs, higher energy prices, or possibly inclusion of other watershed-specific benefits. If energy costs rise or stormwater protection becomes more of a public priority – both highly plausible possibilities – then green roofs become more economically attractive.

Green roofs can provide both private and public benefits and should be included as a potential tool in watershed management manuals for use in highly developed areas. Architects, stormwater professionals and watershed planners can only benefit from having more options to alleviate the environmental impacts of urbanization. An assortment of techniques allows for interested parties to use the practices most effective given their particular location, goals, and resource constraints. As areas continue to become more highly urbanized, reconciling development interests and environmental concerns is essential. The greater the number of practices available to accomplish this goal, the easier it will be to reconcile this future conflict between the built and natural environment.

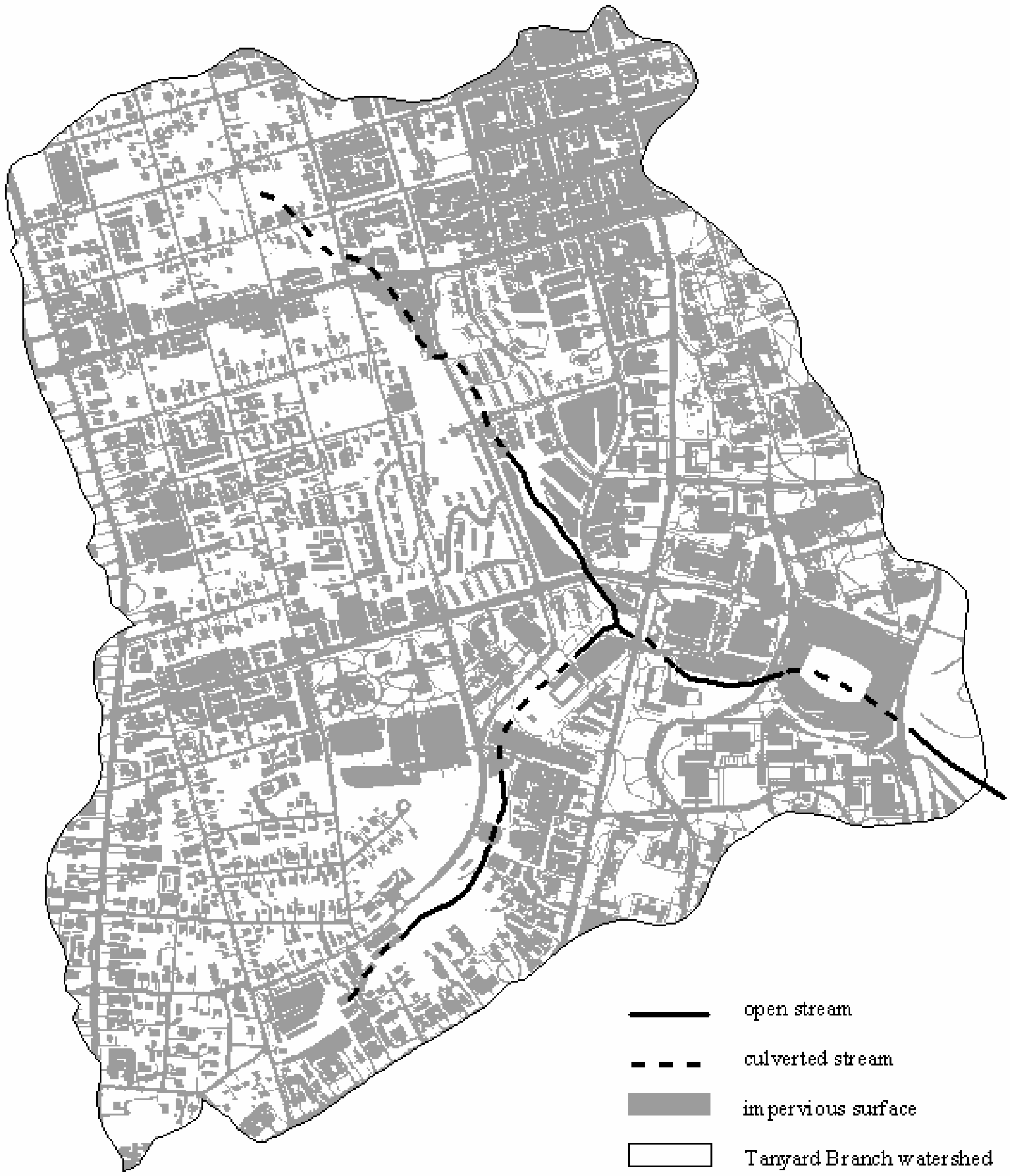


Figure 4.1. Tanyard Branch watershed impervious cover and stream network

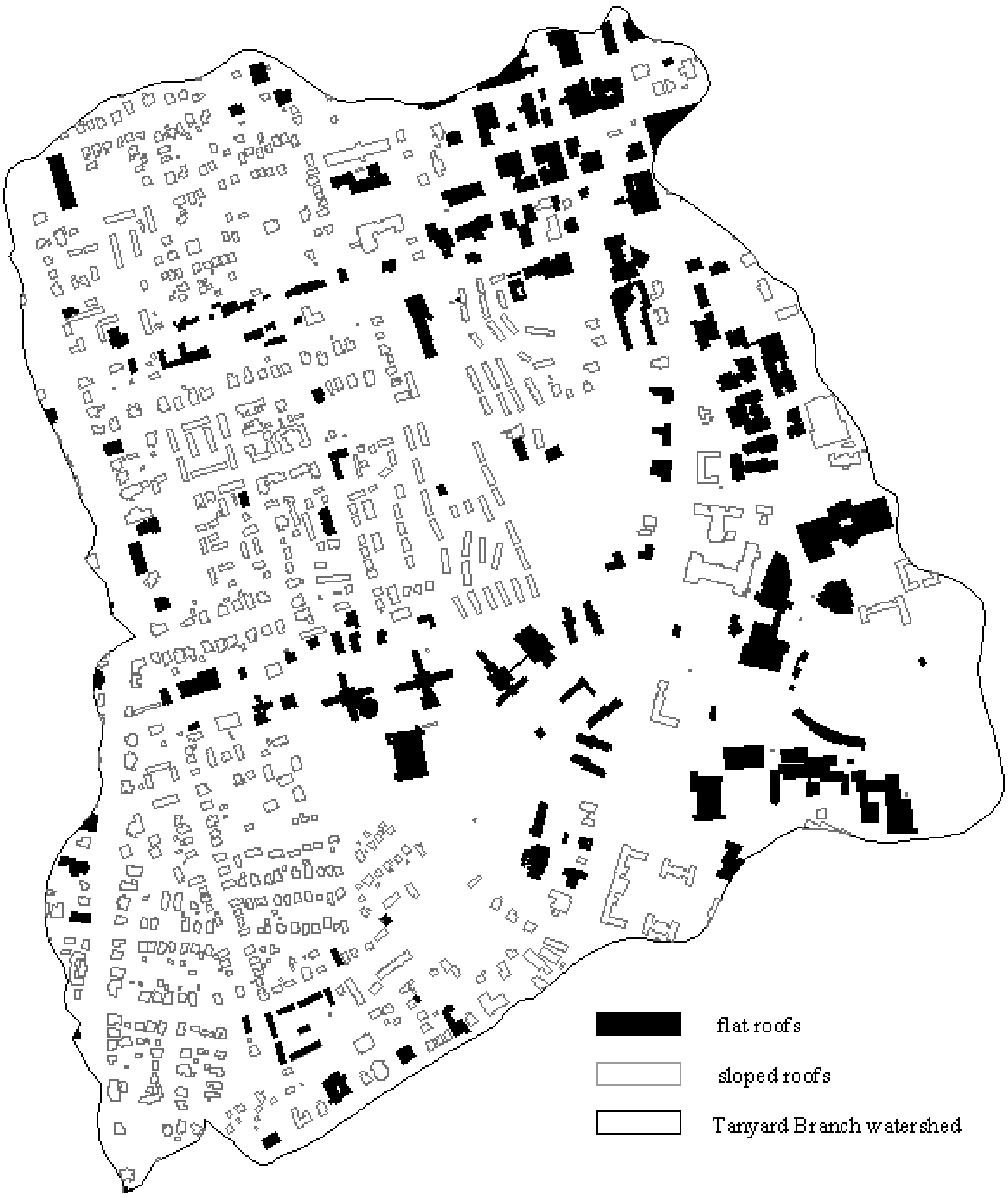


Figure 4.2. Rooftops in the Tanyard Branch watershed

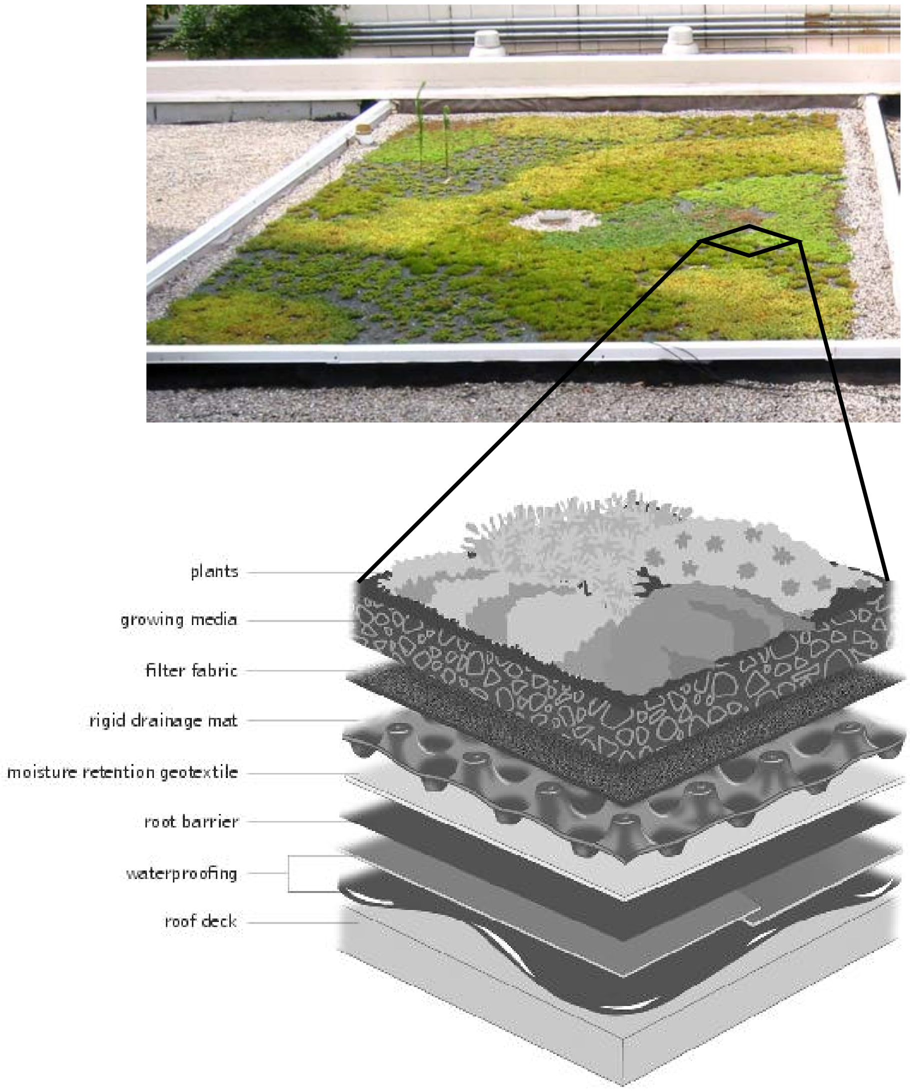


Figure 4.3. Green roof test plot and layer cross-section

Baseline scenario assumptions

Building
- all flat roofs are built-up roofs with gravel ballast
- reroofing cycle of twenty years
- reroofing occurs for all roofs at year zero and year twenty

Society
- need additional stormwater retention
- NOx market for emission reduction

Private
- existing stormwater utility fee
- insulation as required by local building codes

↓

Green roof scenario assumptions

Building
- all flat roofs are extensively greened with 7.62 cm of growing media
- reroofing cycle forty years
- green roofing occurs for all roofs at year zero

Society
- green roof stormwater storage of 4.27 cm
- less electricity used from increased green roof insulation
- air quality improvement from green roof installation

Private
- water quality storage credit for stormwater utility fee
- energy savings from insulation provided by green roofs
- NOx tradable credits

Figure 4.4. Modeling assumptions for private and social BCA

Table 4.1. Benefits from extensive green roof systems

Category	Benefit	Quantified?
Construction and maintenance	-double the roof life	yes
Stormwater management	- storm sewer pipe size reduction - reduces need for alternative stormwater BMPs - stormwater utility fee reduction	yes
Energy and insulation	- additional insulation - energy savings	yes
Air quality	-nitrogen oxide uptake	yes
Habitat/greenspace	-increase bird and insect habitat	no
Urban heat island	-reduction in ambient air temperatures	no

Table 4.2. Costs and benefits per square meter of roof

		Year	Unit values ($/m^2)
Cost			
	TR construction and maintenance	0,20	83.78
	GR construction and maintenance	0	155.41
Social benefits			
	Avoided stormwater BMP cost	0	9.06
	Energy	1-40	0.37
	Air quality	1-40	0.11
Private benefits			
	stormwater utility fee credit	1-40	0.04
	Energy	1-40	0.37
	Air quality	1-40	0.11

Table 4.3. Additional green roof unit construction costs

	Cost range ($/m^2)	**Cost used ($/m^2)**
Specialized roofing material	5.92 – 32.61	32.61
Growing media	5.62 – 6.78	6.59
Plants (21 plugs/m^2)	9.69 – 10.12	9.69
Crane rental	14.90	14.90
Labor	7.84	7.84
Total	**43.97 – 72.25**	**71.63**

Table 4.4. Avoided cost of urban BMPs (source: EPA, 1999)

BMP	Cost ($/m^3 treatment)	Total cost ($) using flat green roof storage in Tanyard Branch
bioretention area	232.37	1,752,593.21
porous pavement	141	1,063,461.04
sand filter	263.09	1,984,319.06
equal distribution of the three BMPs	212.15	1,600,124.44

Table 4.5. Stormwater utility benefits by building type

Building type	**Benefit ($/m²/yr)**	**Total annual benefit in Tanyard Branch ($)**
commercial	0.04	3306.65
government	0.04	3908.66
multi-family residential	0.04	1,003.02
single family residential	0.08	28.47
Total		**7485.95**

Table 4.6. Energy benefits associated with green roofs

Benefit	
Building energy savings (kwh/yr)	4222.56
Energy cost ($/kwh)	0.08
Building energy savings ($/m^2/yr)	0.37
Total annual savings in Tanyard Branch ($)	**65,871.73**

Table 4.7. Conservative green roof social benefits ($) at the watershed scale

Green roof benefit	Unit benefit ($/m^2)	4% discount Rate
Avoided BMP cost	9.06	1,600,124.44
Energy	0.37	1,306,318.84
Air quality	0.11	377,046.09
Total social benefits	**9.54**	**3,283,488.37**

Table 4.8. Conservative green roof private benefits for a 929 m^2 roof

Green roof benefit	Unit benefit ($/$m^2$)	4% discount Rate ($)
Stormwater utility credit	0.04	780.80
Energy	0.37	6870.53
Air quality	0.11	1983.06
Total private benefits	**0.52**	**9634.38**

Table 4.9. Comparison of green and conventional roof net present value (NPV)

	Private roof ($)		**Public watershed ($)**	
	conservative	average	conservative	average
Green roof costs	144,378.20	108,474.13	27,451,153.64	20,624,589.43
Green roof benefits	9634.38	19,040.24	3,283,488.37	5,077,495.58
Green roof NPV	134,743.80	89,433.89	24,167,665.27	15,547,093.85
Conventional Roof NPV	113,352.95	113,352.95	21,552,206.10	21,552,206.10
Green/black roof cost ratio	1.19	0.79	1.12	0.72

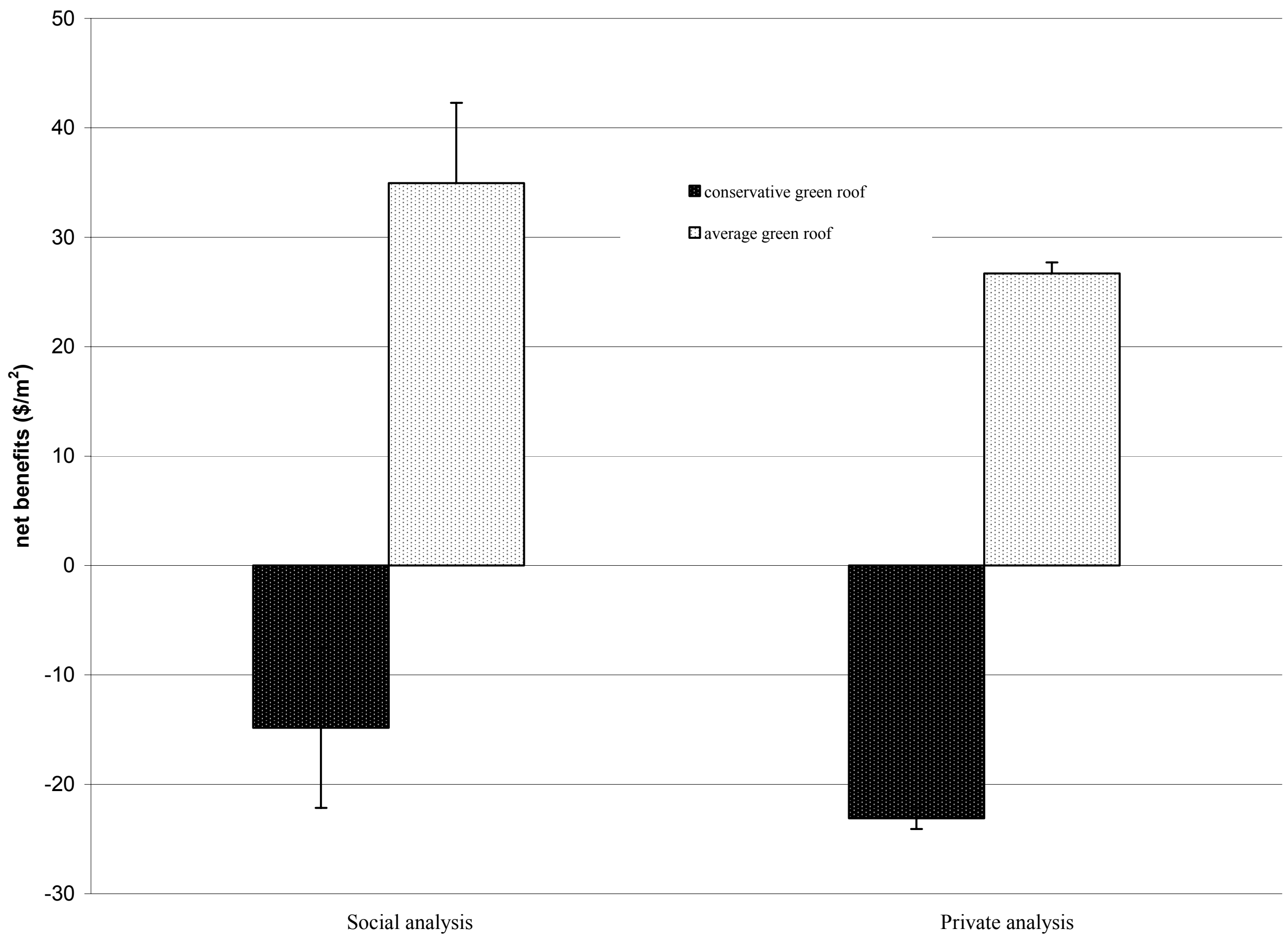


Figure 4.5. Comparison of conservative and average net benefits for private and social green roofing scenarios

CHAPTER 5

ESTABLISHING GREEN ROOF INFRASTRUCTURE THROUGH ENVIRONMENTAL POLICY INSTRUMENTS[1]

[1] Carter, T. and Fowler, L. To be submitted to *Journal of the American Planning Association*

Abstract

Traditional construction practices provide little opportunity for environmental remediation to occur in urban areas. As concerns for environmental improvement in urban areas become more prevalent, innovative practices which create ecosystem services in cities will be in higher demand. Green roofs are a prime example of one of these practices. This study evaluates existing international and North American green roof policies and distills the salient features common to successfully implemented green roof strategies. These features are then applied in the jurisdiction of Athens, GA. Green roof overlay zones are important for prioritizing areas of the jurisdiction where green roofs will be most efficiently function. Financial incentives in the form of density credits and stormwater utility fee credits also help overcome the barriers to entry of the new technology. Demonstration projects and a commitment greening roofs on publicly-owned buildings are an effective way of establishing an educated roofing industry and experienced installers for future green roof construction.

INDEX WORDS: green roof, environmental policy, urbanization, designer ecosystem

Introduction

Urban land area in the United States is projected to increase to 8.1% of total land area by the year 2050 (Nowak and Walton, 2005). Urbanization is a phenomenon that affects the environment in profound ways. One of the most profound effects is that the ecological processes in urban areas can be irreversibly altered and the ecosystem services provided by these processes are often lost (Farber et al, 2006). Covering the ground with impervious surface, a ubiquitous feature of urban areas, greatly reduces the infiltration capacity of the soil and dramatically alters urban hydrology causing increased flooding, aquatic ecosystem degradation and water quality impairment (Paul and Meyer, 2001). The services provided by the soil are costly to replace. Conventionally engineered stormwater systems implemented in urban areas only function to reduce flooding while exacerbating the other environmental problems associated with urbanization. Erosion of stream bed and banks from high storm flows, elevated pollutant transport capacity during storm events and the culverting and burying of urban headwater streams are all common results of traditional stormwater management.

One way to prevent this type of environmental decline in urban areas is to simply preserve patches of land in cities for parks and other green space, thus maintaining many of the ecosystem services in these isolated areas (Pincetl and Gearin, 2005). Another method is to develop engineered systems which mimic and replace services which have been altered due to the impact of human development. While theoretically there is nothing inherently inferior about constructed systems, the complexity and multi-functional components of undisturbed environments are difficult to replicate. Investing in the natural capital of natural systems, such as protecting a watershed to preserve water quality, rather than built capital is often cost effective as well (Salman, 2005).

Heavily developed urban areas can either be written off as degraded and environmentally impotent, or they can be viewed as opportunities for creating environments and ecosystem services where none currently exist. Engineering areas to allow for additional stormwater infiltration, incorporating biological systems directly into a building, and creating habitat corridors to connect existing green space can allow for a more harmonious interaction between the built and natural environments. These "designer ecosystems" are becoming an important component of the urban landscape (Palmer et al, 2004) and can function not only ecologically, but also as urban ecological research sites, public education venues, and potentially add aesthetic value (Felson and Pickett, 2005).

One example of these designer ecosystems is vegetated or green roofs. Green roofs typically contain layers of engineered growing media and drainage materials which are incorporated into a roof membrane and support plant communities which are tolerant of the extreme weather conditions found on rooftops. Researchers have likened green roofs to rock outcrop ecosystems and have begun to treat them as habitat templates where unique biotic assemblages adapted to the harsh rooftop conditions are expected to colonize (Lundholm, 2005)

Green roofs fall into two general categories: intensive and extensive. Intensive roofs contain deep layers of growing media, can support diverse plant communities, and are found on structures such as underground parking garages which can support their additional weight. Extensive systems have a much thinner profile, are limited in the options for plant diversity and can easily be retrofitted onto many existing structures. Extensive systems are by far the most common in Germany due to the ease of implementation and relatively low cost (Harzmann, 2003). Extensive green roofs are the most likely to become widespread in North America due to existing market conditions where the additional expense of green roofs and limited installation experience has relegated them to very specialized applications (Beattie and Berghage, 2004).

There are numerous social and private benefits provided by intensive and extensive green roof systems. Stormwater retention is one of the most frequently cited environmental benefits. Green roofs retain significant amounts of rainfall from small storm events which would typically be discharged quickly into the nearest receiving water body or sewer system (Carter and Rasmussen, in press). This retention may prevent nuisance flooding and streambed and bank erosion through a reduction in peak discharge rates and volumes. The pollutant transport capacity of stormwater is also reduced when discharge rates are lessened. Reduction in the roof's temperature through shading and evaporative cooling lessen the heat flux into the building resulting in decreased HVAC costs. Air quality is also improved as the plants will uptake NO_x, a common greenhouse gas, from the atmosphere. Aesthetic improvements, habitat provision, increased urban biodiversity and sound insulation are all other benefits that green roofs can provide (Peck et al, 1999)

Installing green roof systems involves additional expense and risk for the North American building owner due to the novel nature of these systems. Currently, extensive green roofs add anywhere from \$5-10/ft^2 onto roof construction costs depending on site conditions. Total costs, including waterproofing, for extensive green roof systems average \$12-18/ft^2. When the entire life cycle costs of the roof are calculated, however, the green roof's private and public benefits such as stormwater retention, building energy savings and improved air quality offset much of the additional up-front roof construction costs. Some studies show a net savings over the life of the roof when green roofs are used (Wong et al. 2003).

Public benefits are, by definition, not fully realized by the party bearing the cost of the green roof installation and this creates a need for public intervention through the development of green roof policies. The goal of this paper is to evaluate the best policies for establishing a green roof infrastructure given the considerable spatial variation, building types, and land cover found in urban areas. The authors first look at the legal background for green roof policies in countries with green roof programs. Existing policies that have been developed internationally and more recently in select major North American cities are then evaluated. These existing policies fall into a number of distinct categories including: direct and indirect regulation, direct and indirect financial incentives, and funding of demonstration or research projects. Advantages and disadvantages of each category are discussed as well as key features of existing green roof policies. Finally, a model policy is developed for the jurisdiction of Athens, Georgia to demonstrate the importance of customizing green roof policy to local conditions.

Legal foundation for green roofs at the federal level

Germany

The country which has led the way in green roof policy and implementation is Germany and an examination of their national regulations can shed some light on what made this possible. The Federal Building Code (FBC) and the Federal Nature Conservation Act (FNCA) contain sections which are of particular importance to the development of green roof policy.

Federal Building Code

Section 1 of the FBC outlines the goals for urban land use planning specifically addressing environmental concerns:

> (1) Land shall be used sparingly and with due consideration; the extent to which it is sealed by development shall be kept to a minimum.

According to the FBC, land use plans must both avoid impacts on nature and provide counterbalances for the environmental impact that is caused. Counterbalance measures are to be undertaken within the area of the landscape where development takes place. This federal regulation clearly establishes a system where development that has harmful environmental impacts must be mitigated with practices which lessen that impact. Green roofs, while not explicitly mentioned, satisfy the counterbalance provision as they provide remediation at the location where the impact is taking place and help reduce intrusion into other areas of the landscape.

Federal Nature Conservation Act

Section 3, Articles 18 and 19 of Germany's Federal Nature Conservation Act regulate "Interventions in Nature and Landscapes". Interventions in nature and in landscape are defined as:

> (1)…changes to the shape and appearance or utilization of land or changes to the groundwater table with its close correlations to inhabited soil compartments that may significantly impair the ecosystem, or the natural scenery.

Obligations on the intervening party are imposed including compensation and offsets which restore ecosystem function in an equivalent manner. This is commonly referred to as the Intervention Rule and the regulations establish a system identifying interventions and compensations relating to environmentally degrading activity. The provision for offsets in the FNCA is parallel to the counterbalance provision in the FBC with green roofs functioning as equivalent environmental offset measures.

Other German Federal Statutes

Two other German federal statutes contain provisions directly relating to green roofs as a tool for mitigation:

Article 31 of the Federal Water Act

(5) During development natural retention areas should be maintained, natural run-off conduct not changed greatly, biotic communities typical of the natural area conserved and other major negative changes to the natural or semi-natural state of the body of water avoided or, if this is not possible, balanced out.

Article 5 of the Federal Soil Protection Act

Where provisions of construction law do not define the competence of the authorities, the Federal Government shall be authorized… to obligate property owners…to maintain or restore the functional capacity of the soil within the meaning of Article 1, to the possible and reasonable extent, on land that is to remain unused in the long term and whose sealing would violate determinations under planning law.

United States Federal Statutes

In the United States, land use regulations were traditionally enacted at the state or local level. The rationale was two-part: only state and local governments have the authority to exercise police powers to protect public health, safety and welfare and decisions regarding land use are best made at a more local level given variations in resources and site conditions across the country. This began to change with Congress' recognition that water resources are being compromised in the face of state and local failure to manage land uses causing nonpoint source water pollution and the courts' holdings that the Commerce Clause provides Congress authority to regulate interstate waters.

Stormwater management provisions in the Federal Water Pollution Control Act (FWPCA) have direct application for green roof systems. Section 402 of the Act establishes the National Pollution Discharge Elimination System (NPDES) permitting process which includes permits for stormwater runoff. Under Phase I of the program, NPDES stormwater permits are required for municipal storm sewer systems that serve a population of over 100,000, construction activity disturbing five acres of land or greater, and various types of industrial activity. Phase II expands the coverage of NPDES permits to operators of municipal stormwater systems in smaller urbanized areas and construction activities greater than one acre and less than five acres of land. Approval for both Phase I and Phase II permits are contingent upon the development of stormwater management programs that include provisions to treat stormwater runoff using best management practices. These best management practices include green roofs.

Section 303(d) of the FWPCA requires states to create water quality standards for receiving water bodies and develop total maximum daily loads (TMDLs) for those water bodies not meeting their assigned standard. TMDLs may apply to both point and nonpoint sources. Controls such as green roofs may be part of TMDL plan to reduce pollutant loading in a specified water body particularly impacted by stormwater runoff.

Additionally, Section 319 of the FWPCA addresses nonpoint source pollution controls including stormwater management. This section requires states to identify waterways which cannot meet water quality standards without control of nonpoint source pollution. The categories of nonpoint pollution sources must be identified and the state must recommend best management practices for control of these sources of pollution. Section 319 also establishes a grant program whereby federal and state funds are allocated to local governments and other entities to fund nonpoint source pollution control. As of 2003, eight green roof projects had been funded from Section 319 in Arizona, Rhode Island, Oregon, Illinois, Pennsylvania, and Maryland (Goo, 2004).

Another federal regulation applies to green roof stormwater retention performance and their ability to mitigate combined sewer overflows (CSOs). The CSO Control Policy codified at Section 402(q) of the FWPCA requires that communities serviced by combined storm sewer systems implement BMPs as part of a pollution prevention program to reduce contaminants in CSOs. Research has shown that green roofs have the potential to reduce overflow volumes by more than 18% (Doshi et al, 2005). Green roofs could therefore be a key component in the CSO control plan for local jurisdictions applying for their pollutant discharge permits.

Municipal and community level green roof policies

At the lower levels of government, policies have been specifically crafted to encourage new green roof projects. This is the level where the most explicit green roof policies can be found. There are a number of general categories of green roof policies which directly and indirectly encourage new green roof installations. Some policies take the form of a "command and control" approach through performance or technology standards while others utilize a market-based approach using tax incentives or government subsidies. When determining which type of approach to use, it is important to recognize whether the costs of implementation are homogenous across the industry or if there is a significant degree of heterogeneity. If costs are relatively similar, then a policy based on standards can be just as efficient as market-based approaches (Revesz and Stavins, 2004).

Technology standards include building code requirements that mandate the use of green roofs over all or part of a building's rooftop. Performance standards specify an amount of on-site stormwater retention which may be met through the use of green roof technology. Direct economic incentives involve subsidies both specifically for new green roof installations as well as funding urban greening programs that include green roofs as an urban greening practice. Density bonuses for roof greening and stormwater fee credits are common forms of indirect economic benefits.

Technology Standards

One option to encourage green roof implementation is to directly mandate in the building code that all buildings of a certain type must green all or part of their roof. Public buildings or large commercial buildings with flat roofs are often identified as candidates for this regulation. Design specifications may also be included such as the depth of growing media, amount of plant coverage, water retention capacity, and/or roof surface reflectance.

This technology standard approach has been implemented in Tokyo, Japan where private buildings larger than 1000 m^2 and public buildings larger than 250 m^2 are required to have 20% of the rooftop greened. Due to this ordinance, 54.5 ha of rooftops have been greened in the city as of January 1, 2005 (http://www2.kankyo.metro.tokyo.jp/kouhou/env/eng/index.html). The city of Linz, Austria requires green roofs on all new buildings larger than 100 m^2 and a slope of up to 20% as well as the roof surfaces of all underground structures such as subsurface parking decks (Ngan, 2004).

Two North American municipalities have also recently adopted green roofing requirements in their building policy. The city of Toronto, Canada approved a policy stating that, "…where feasible and practical, green roofs with a coverage of 50-75% of the building footprint be constructed on all new City-owned buildings…on existing City-owned buildings…when roofs are due to be replaced" (Toronto City Clerk, 2006). A green building policy was also enacted in Portland, Oregon which mandates that all new city-owned facilities include a green roof with 70% coverage unless the green roof is impractical (PDC, 2005). In both Toronto and Portland, there is no additional policy guidance as to what constitutes feasibility or practicality. Toronto's green roof projects must fit within the City's capital and operating budgets and occur on roofs which have low-slopes, adequate structural capacity and are easily maintained. In Portland's case, a train station owned by the city which normally would have required a green roof was exempted because it is on the National Historic Registry.

Performance Standards

A number of jurisdictions have identified sections of their city or areas of new development to be bound to tighter environmental controls. These environmental controls are based on stormwater management goals, urban greening requirements, or rooftop reflectance values. In Berlin, an inner-city area named Potsdamer Platz was redeveloped after decades of neglect. The Berlin city council passed a mandate requiring the project to manage 99% of its stormwater on-site. The development used a combination of stormwater tools, including extensive green roofs, to accomplish this goal (Earth Pledge, 2005).

At a broader scale in North America, a number of states have adopted stormwater management manuals which identify stormwater management standards primarily for new development. The Georgia Stormwater Management Manual (GSMM), for example, creates four unified stormwater sizing criteria for jurisdictions in the state in need of a National Pollutant Discharge Elimination System (NPDES) permit. These standards include: capture and treatment of the runoff from 85% of the storms that occur in one year, extended detention of the one-year storm event released over a period of 24 hours, control of the post-development peak discharge rate to predevelopment rate for the 25-year event, and managing the impacts of the 100-year storm event through detention controls and/or floodplain management (ARC, 2001). To accomplish these standards, the GSMM contain a section of recommended structural stormwater BMPs. While green roofs are not currently included in this section of Georgia's manual, other states such as Pennsylvania, New Jersey, and North Carolina have included green roofs in their structural BMP section and it is expected that as green roofs become more common, they will be included in future stormwater manuals.

Urban areas are notorious for a lack of green space with new attention being paid to strategies that integrate urban infrastructure and green areas (Pincetl and Gearin, 2005). Urban greening and green infrastructure performance standards can also promote the use of green roofs. Areas of a city may be prioritized or a simple standard may apply across a particular jurisdiction. Urban greening policies require that a simple percentage of the site must remain undisturbed or a maximum amount of the site that may be covered in impervious surface.

A more sophisticated urban greening policy which encourages green roofs exists both in Berlin, Germany and Malmö, Sweden and is generally known as the Biotope Area Factor (BAF). The objective of this policy is to improve an ecosystem's functionality and promote the development of biotopes in the city center (www.stadtentwicklung.berlin.de). BAF is defined as:

$$\text{BAF} = \frac{\text{ecologically-effective surface areas}}{\text{total land area}}$$

Different surfaces have different BAFs according to the ecosystem services provided such as stormwater retention, habitat creation, or connection with existing environmental features of the site. BAF targets are developed based on the type of land under development, the amount of additional construction on the site, and whether it is new construction or an extension of existing coverage. The target BAF is then achieved using a combination of practices which are weighted according to their individual BAF. As can be seen in Table 1, green roofs have one of the highest weighting factors of all land uses.

A final green roof performance standard is found in areas which require minimum reflectivity standards for rooftops. This standard derives from a well-known phenomenon that occurs in urban areas known as the urban heat island effect where temperatures of urban areas can be 6-8 °F hotter than the surrounding landscape due to dark impervious surface cover such as asphalt rooftops (Bornstein, 1968). Roofing materials which have lower roof reflectivity help to mitigate the thermal impact of developed area. The U.S. EPA has created an Energy Star labeling system for roofing materials which have a reflectance value of greater than .65 and the Leadership in Energy and Environmental Design (LEED) Green Building Rating System assigns points for using Energy Star rated roofing products.

Green roofs can be used as a surrogate for these highly reflective roof coatings due to the evaporative cooling potential of the plants and growing media. The city of Chicago has directly incorporated green roof incentives into their municipal energy code for the purposes of mitigating the urban heat island:

> 18.13.303. Urban heat island provisions. The reflectance and emittance requirements…are intended to minimize the urban heat island effect
> …
> 1. The portion of the roof that is covered by a rooftop deck covering 1/3 or less of the aggregate area of the roof, or a rooftop garden, or a green roof, is exempted from the requirements of this section.

Direct Financial Incentives

Another policy tool for encouraging green roof systems is the use of direct and indirect financial incentives. One of the most commonly implemented green roof financial policies in Germany is the use of a subsidy to encourage new green roof construction. These types of direct financial incentives help overcome the barrier of adopting new technology. Particularly in the North American market where the green roof industry is not robust, reducing the market friction is important to encourage socially desirable behavior (Revesz and Stavins, 2004).

In general, green roof projects can qualify for a subsidy by being built to certain specifications such as a minimum depth of growing media, minimum maintenance agreements, and minimum vegetation coverage. The subsidy is then credited in a $\$/m^2$ amount. German subsidies occur at the state and municipal levels of government and they typically range from 10-50% of initial construction costs, (Ngan, 2004). Approximately 50% of German cities offer some form of direct subsidy to building owners for installing green roof systems (www.greenroofs.com).

Berlin enacted a green roof subsidy program from 1983-1997 which reimbursed residents approximately 50% of green roof construction costs and resulted in approximately 63,500 m^2 of green roofs built in the city (Earth Pledge, 2005). A region in Germany, North Rhine Westphalia, currently has a subsidy for practices controlling stormwater. The subsidy includes 15 €/m^2 for removal of impervious surfaces, 15 €/m^2 for infiltration systems and 15 €/m^2 for green roofing insulation, drainage layers, substrate, and plants. The green roofs eligible for the subsidy must also have a runoff coefficient of at least 0.3 according to German national green roof guidelines (FLL, 2002).

In the United States, there are currently no programs offering direct subsidies for the unit costs (\$/m^2) of green roof installations across a jurisdiction. Instead, there are green roof grant programs which offer lump sum payments under a competitive selection process. In 2005, the city of Chicago allocated \$100,000 to be distributed to 20 green roof projects on residential and small commercial applications. The projects ranged from an 800 ft^2 vegetable garden to a 1750 ft^2 green roof and selection criteria were based on project location and visibility as well as environmental benefit (www.cityofchicago.org).

Indirect Financial Incentives

The most prevalent green roof policy is the use of some form of indirect financial incentive to support construction of green roofs. Of these indirect incentives, a credit towards a municipality's stormwater utility fee is popular for encouraging green roof installation.

Stormwater utilities are typically based on the amount of impervious surface which is found on a given site. This amount of imperviousness is often assumed to occur consistently across zoning or land use categories so a base fee is established per amount impervious area on a typical site. Residential land use may be used to establish the fee structure with all other land uses being charged a fee based on their impervious surface relative to a typical residential site. Mitigation measures such as green roofs which offset a site's stormwater contribution are given credit towards a portion of the stormwater utility fee. Stormwater utilities are being used increasingly in the United States to fund stormwater programs with some researchers estimating there will be over 2500 utilities in the U.S. in the next decade (Woolson, 2004).

Portland's Clean River Incentive and Discount program (CRID) illustrates how greenroofs can be used to offset a stormwater utility fee. The city's base stormwater management charge for single family residences is $14.26 per month. CRID allows for up to a 35% reduction of this stormwater charge depending on the effectiveness of the site owner's private stormwater management. Preliminary reports show that a green roof covering over 70% of the rooftop will allow the site owner to receive the total amount of credit available under the program (Liptan, 2003).

Another indirect incentive is allowing an increase in building density bonuses when green roofs are installed on the building. This policy is implemented in both Portland and Chicago, the two major metropolitan areas in the United States leading the way in green roof installations. The basic form of the policy involves designating areas of the city which are eligible for bonus applications and then determining the amount of bonus for each ft^2 of green roof. In the case of Portland, for green roofs that cover up to 30% of the roof area, one ft^2 of bonus is allowed for each square foot of green roof. For green roof coverage of up to 60% of the roof area, two ft^2 of bonus is allowed for each ft^2 of green roof. For green roof coverage of greater than 60% each ft^2 of green roof will allow three ft^2 of bonus (Liptan, 2003).

Chicago has also incorporated green roofs into section 17-4-1015 of their zoning ordinance which allows for floor area bonuses to developers who provide public amenities that improve the quality of life for the public. The following formula is used when calculating the floor area bonus in Chicago:

Bonus floor area ratio (FAR) = (area of roof landscaping in excess of 50% of net roof area ÷ *lot area)* * 0.30 * Base FAR.

Minimum criteria for buildings to be eligible for the bonus include location within specific districts where the policy applies, minimum coverage of the green roof over the net roof area, provisions for maintenance over the life of the building, and demonstration that the building can support the additional weight.

<u>Advantages / Disadvantages of green roof policies</u>

There are distinct advantages to utilizing certain types of green roof policies over others based on the goals of the green roof program, landscape features of the jurisdiction, and institutional support. Direct financial incentives in the form of subsidies have the advantage of building owners receiving direct compensation for initial construction costs of the roof, which is often the limiting factor in determining whether or not to install a green roof system. Jurisdictions must have adequate funding sources to provide this subsidy, however, and many of these sources may vary from year to year based on annual budgets. In several jurisdictions in

Germany, green roof subsidy programs were implemented for a number of years but were eventually terminated because of budget constraints (Ngan, 2004).

Indirect financial incentives and performance standards have the advantage of being voluntary, favoring those owners who can install green roofs in a cost-effective manner based on their site conditions. This may be accomplished in both new construction and retrofit situations. The disadvantage is that it is difficult to guarantee green roofs will be installed, particularly when other more familiar management practices may also be used to accomplish the same environmental goal.

Mandating green roofs through the building code provides the highest level of insurance that buildings which qualify for roof greening will, in fact, install a system as defined by the agency in charge of oversight. The standards must clearly define installation procedures guaranteeing builders will install quality green roof systems. Some drawbacks to this approach are that it is likely to be politically unpopular and this is why it is sometimes implemented only on publicly owned buildings or buildings receiving public funds. An additional disadvantage to the technology standard approach is that it can stifle innovation as installers are bound to rigid criteria for each green roof they install.

<u>Prompting standards and features of successfully implemented green roof policies</u>

A review of the policies of those jurisdictions currently promoting green roofs indicate there are some conditions necessary for the adoption of green roof policy and other conditions that should be addressed in the policy itself.

Environmental concern in highly developed areas

Green roof policy is always driven by some environmental concern found in urban areas. Some of the green roof policies are embedded in green building resolutions and therefore environmental concerns stem from the problems associated with development and construction practices in general, not specifically rooftop contributions. These issues cover a wide spectrum from air and water pollution, deforestation, toxic emissions, climate change, depletion of natural resources, energy consumption, and solid waste disposal. Three environmental issues that are directly used to justify green roof policy are the effects of stormwater runoff in urban areas, thermal impacts of traditional rooftops and the lack of greenspace in highly developed areas. Without one of these three drivers, there is little footing for roof greening initiatives.

Well defined standards for qualifying green roofs

In Germany, the Landscaping and Landscape Development Research Society (FLL) has developed a comprehensive green roof standard book called the "Guideline for the Planning, Execution and Upkeep of Green-Roof sites". This guide, which has been translated into English, provides a standard for German green roof implementation which both the green roof installers and the government regulators can refer to when developing their green roof projects, reviewing submitted plans, and creating incentives for new implementation.

Uniform green roof standards have only recently begun to be developed in the U.S. The jurisdictions which have begun green roof policies use various standards for what constitutes a green roof. Standards should address minimum continuous coverage of the growing media, maximum slope of the roof, stormwater retention requirements, minimum depth of growing media, identification of qualifying buildings, and maintenance agreements.

Targeted areas for roof greening

An important feature of green roofs for environmental remediation is that they are limited in their application for society to receive the maximum benefit they can provide. Green roof policies are most effective in areas where a drainage basin contains high proportions of rooftop impervious area, or contains high levels impervious area. In less urban areas, other management strategies may be more easily implemented. This has meant that green roof policies are found in cities with large populations and dense urban cores where high levels of impervious surface are found. The technology is widespread and well-established throughout Germany with 14% of flat roofs in the country being greened in 2001 (Earth Pledge, 2005). Outside of Germany, leading cities promoting green roofs often have dense populations and established urban centers including: Tokyo, London, Toronto, Chicago, and Portland.

Population size is not a prerequisite for a drainage area to contain high levels of rooftop or total impervious surface area. Commercial sites containing "big box" stores, urban centers of small municipalities, or industrial sites all can fit the mold for a targeted green roof policy to be efficiently implemented. Identifying whether the policy applies to new and/or existing structures can further refine the type of policy used.

Advocacy groups or local individuals to promote green roofs

Both European and North American green roof policies were initiated by a small group or number of individuals. In Germany, modern green roofs began in the 1960's when researchers began to investigate some of the rooftop vegetation which had begun to naturally occur around Berlin. This research and subsequent public and private interest led to the formation of the Landscaping and Landscape Development Research Society (FLL) in 1975 which helped solidify the core of green roof interests in the country and paved the way for innovation both in the construction of green roofs and in the policies used to promote them.

In North America the largest advocacy group is the Toronto-based nonprofit organization named "Green Roofs for Healthy Cities" (GRHC) which was founded in 1999 after the release of a green roof feasibility study by the group's founders, a consortium of public and private researchers. For the past four years the group has organized the largest green roof conference in North America which brings together researchers, policy makers and members of the green industry to explore the current and future state of roof greening around the world.

Individuals also play a crucial role in establishing green roof programs in their communities. A classic example of the power of the individual is found in Portland, Oregon where in 1994 an employee of the Portland Bureau of Environmental Services took an interest in green roofs, built some test plots over his garage and provided data to the city which spawned larger test plots. This has blossomed into Portland becoming one of the leaders in green roof installations in North America including being the host city for GRHC's annual conference in 2004.

Institutional authority to oversee green roof program implementation

In all cases in North America, the jurisdictions which have implemented green roof policies have sufficient institutional support for staffing and technical assistance. In Toronto, the policy development process specifically identified "green roof resource person[s]" to be housed in five separate divisions (Toronto City Clerk, 2006). While technical knowledge can often be left to the private firms responsible for green roof installations, adequate knowledge must be present in the regulatory agency's staff so that green roof installations will meet the goals expressed by the enacting legislation.

<u>Application of green roof policy: Athens, GA</u>

Study Site Background

In order to apply the lessons learned from existing green roof policies, the jurisdiction of Athens, GA was selected as a test case. Athens is located in northeast Georgia approximately 100 km east of Atlanta and contains a population in 2005 of approximately 108,000 (www.athensclarkecounty.com). Athens-Clarke County is a unified city and county government. Land use in the watershed is typical of an urban area with high densities of impervious surface in the urban core of the city, commercial areas along major road arteries, isolated industrial parks, residential subdivisions, and designated agricultural zones. The University of Georgia is located in Athens and a large tract of land downtown is dedicated to the campus.

A thin-layer green roof test plot was established on campus in October, 2003 and was monitored for its ability to retain stormwater and mitigate rooftop temperatures (See Carter and Rasmussen, in press and Hilten, 2005 for more details on this study). This type of green roof was designed to be cost-effective and easily replicated and therefore was considered as the model for new green roofs in the watershed. A spatial analysis was performed in the Tanyard Branch watershed, a highly urbanized drainage area near the downtown core of Athens. The amount of rooftop area and the ability of green roofs to mitigate stormwater runoff volumes in drainage areas within the basin was modeled for a number of small and large storm events. This analysis demonstrated that in Athens both zoning class and individual parcels are the most appropriate scale for distinguishing stormwater retention performance of green roof systems. When the analysis is performed at larger scales, such as sub-watershed or watershed, the stormwater retention effect of the individual roofs becomes diluted with the other land coverage.

Athens' stormwater system is separate from its sanitary sewer system. This type of infrastructure has advantages and disadvantages for green roof implementation. The advantage is that it allows for a stormwater utility to be easily created as maintenance and repair of the stormwater infrastructure is often contained in a stormwater department with an independent budget allocation. The disadvantage is that one of the quantifiable benefits that can be realized with green roofs is the reduction of combined sewer overflows due to stormwater volume attenuation.

The ACC Mayor and Commission voted to create a stormwater utility fee in 2004. This utility charges parcel owners a fee based on the amount of impervious surface on the parcel and zoned land use. The fee is divided into three parts, a base fee, stormwater quantity fee, and stormwater quality fee. If parcel owners can demonstrate they have instituted practices that reduce either the stormwater quality or quantity, credit will be given on their bill. Practices must be approved by a stormwater engineer according to specifications found in the Georgia Stormwater Management Manual (GSMM). The program is used to fund ACC's federally mandated stormwater management program.

General building permit fees are based on the value of the proposed construction. Currently the fees associated with construction contain no stipulations for credits based on environmentally beneficial construction practices. The Athens-Clarke County zoning code identifies limits to the floor area ratio (FAR) for commercial buildings depending on zoning class. FAR is the result of dividing the total floor area of a structure by the area of the lot on which it is located. For the downtown core of the city, maximum FAR is 5.0 whereas for areas zoned commercial-rural, the maximum FAR is .25 (Table 2).

Policy recommendations

The current institutional framework and landscape characteristics of ACC allows for many green roof policy options to be investigated. It is important before selecting or prioritizing policies in the watershed that the jurisdiction clearly defines the goals it wants to accomplish. In the case of ACC, the recently enacted stormwater utility indicates the jurisdiction considers stormwater management important to both comply with federal regulations and protect the integrity of streams and rivers in the jurisdiction. ACC urban greening initiatives have not focused explicitly on green construction practices with the policy makers in the area placing most emphasis on riparian buffers and green corridors. A notable exception is found in a recent internal policy requiring all public buildings to be designed to meet the minimum standards for LEED certification. This does not necessarily result in green roof construction, however, as four buildings have been completed since the policy went into effect and none have green roofs.

Given these goals and the landscape characteristics of the jurisdiction, the most effective green roof policy in ACC should be both spatially focused and multifaceted. The primary spatial targets for roof greening is the downtown core, commercial and industrial areas. In areas zoned residential or agricultural, impervious surface levels are significantly lower at the parcel level than in the designated target areas. Also, the impervious surfaces which are found on a lot are typically not fully connected to the storm sewer system as they are in more densely developed zones. This lack of direct connection allows for stormwater mitigation to be performed easily using management methods other than green roofs. Other management practices that may be more appropriate in these areas where unsealed land is abundant relative to impervious areas include practices such as bioretention areas, constructed wetlands or infiltration basins.

The primary spatial targets are easily identified on ACC's zoning map. Creation of a special green roof district overlay in these areas would allow for all new and existing development to fall under the same guidelines and receive the same benefits for green roof installation. Specifications for green roof construction in the overlay zone may be as follows:

1) Roofs which are flat or nearly flat (~2% slope) are eligible to participate in the credit programs for roof greening
2) Minimum thickness of growing media is 3" for stormwater retention credit.

3) The vegetation, growing media and specialized roofing layers must be installed according to manufacturer specifications.
4) A green roof maintenance plan must be submitted.
5) While modular green roof systems are allowed, a minimum area of 50% must be greened for roofs to qualify for credit programs

A stormwater utility credit for green roof installation is the second policy recommendation. Since ACC currently allows credits for practices in the GSMM and the GSMM currently does not reference green roofs as a stormwater volume mitigation tool, either an addendum to the GSMM must be created or a change to the credit system must be made to include green roofs as a BMP. Regional supplements to the GSMM as well as other state manuals have included green roofs as a stormwater management practice (www.etowahcp.org) and it is reasonable to consider them as existing in a revised version of the GSMM. A model specification for green roofs which may be included in the manual is included in Appendix A.

In practice, allowing for green roofs to count towards the stormwater volume credit independent of the GSMM may be an easier task. This involves documentation that post-development peak flow mitigation from various storm events will occur. Green roof performance information can be found in recent publications (Carter and Rasmussen, in press) and used to establish a water quantity credit. Crediting stormwater customers with a water quantity credit results in a savings of approximately $1.78/month for average single family homes. Since the fee is based on the size of the property, larger buildings could realize much greater savings. Athens City Hall, for example, would save nearly $27/month in its stormwater utility fee.

The third tier of the green roof policy involves offering floor area bonuses, a form of density credits when green roofs are installed in the green roof overlay zones. This policy will most likely play the largest role in the downtown and commercial areas where lots are small relative to the building footprint and additional floor space may be extremely valuable (Table 2). The density formula is based on Chicago's policy which calculates credits based on the floor area ratio of the zoned property:

FAR bonus = (area of green roof / total lot area) x (0.4) x (current FAR)

In the case of a green roof on a 20,000 ft^2 building in the downtown commercial area entirely covering a lot, the bonus would allow for an additional 2 units of FAR for a total of 7 units thus adding an additional 40,000 ft^2 to the proposed structure.

By creating a voluntary incentive program based on the possibility of increased floor area, it is assumed that the areas with the highest value per square foot of floor area would take advantage of the density credits. This most costly property in the jurisdiction is in the downtown commercial zone. The downtown commercial area is also the part of the jurisdiction with the highest density of impervious surfaces, averaging over 77% total impervious area. This makes green roofs one of the few viable environmental mitigation tools with this incentive program encouraging the tool where green roofs are needed most.

The fourth tier of green roof policy involves the creation of demonstration projects. An important part of encouraging any new technology is to actually use it – to familiarize the public with the fact that technology exists and works in the locality. Builders need opportunities to install the systems and become comfortable with using a new practice. There are currently only three examples in the ACC area where green roofs have been installed. An elementary school had a green roof constructed in the early 1970's as part of an earth building project. The green roof was constructed with topsoil and grasses and is not similar to the highly engineered systems recommended for use in ACC. The other two green roofs are research plots, one of which was previously described and the other is a small 4 ft x 8 ft test plot constructed over a shed at a private residence. The small test plot is being qualitatively monitored for plant survivability with no specialized roofing layers and highly porous growing media.

As described earlier, the commitment to greening publicly owned buildings already exists for new construction in ACC and green roofs may easily be incorporated into this LEED standard or directly mandated for specific buildings. Green roofs can directly earn LEED points through the following categories:

- Reduced site disturbance, protect or restore open space
- Landscape design that reduces urban heat islands, roof
- Stormwater management
- Water efficient landscaping
- Innovative wastewater technologies
- Innovation in design

Green roofs may contribute up to 15 credits under the LEED system depending upon how well the roof is integrated into other the building systems (Kula, 2005).

Mandating roof greening on public buildings also is recommended. Public roof greening should be clarified to include only buildings where green roofs are feasible, meaning the buildings matching stipulations found in the ACC green roof overlay zone guidelines described earlier. This policy would serve a number of purposes. Greening the roofs of public buildings would generate all the positive ecosystem services that green roofs provide on any site. It also would establish local green roof examples which would serve as references for future private installations. Local industry connections would also be established with potential job creation opportunities if the industry expands.

Conclusions

Finding ways to repair the damaged environment in the urban landscape is difficult. The more tools that urban planners, landscape designers, policy makers and engineers have in their proverbial toolbox, the more flexibility they will have to determine what practices may work best given the constraints of the local landscape. Designer ecosystems, like green roofs, fit well with jurisdictions that see the built environment as ripe with opportunities for management.

Throughout urban areas, land uses may vary dramatically from highly impervious to relatively undeveloped. When prescribing environmental management practices, consideration must be paid to the spatial variation within jurisdictions and the appropriate management tools which may vary with location. Green roofs have the potential to provide benefits to both the public and private sectors in certain areas and situations. Because the technology is so new, it should be encouraged with directed policies. Targeted policy development is crucial for efficient allocation of public funds.

Policies at various levels of government have proven successful in promoting the use of green roofs. Federal policies can mandate the control of stormwater or other kinds of environmental protection and provide direct funding through grants or subsidization through tax relief for green roof installation. Local governments can mandate or encourage the use of greenroofs as a means of controlling stormwater or achieving other environmental goals in specific locations or circumstances. Both voluntary private economic policy incentives a direct green roof mandates can be used to encourage green roof installations. Without adequate education and on-the-ground examples, however, the regulated community may have a difficult time changing established roofing practices. By mandating green roof policies for public buildings, jurisdictions can demonstrate their commitment to sustainable building practices as well as provide local green roof reference sites for other builders.

Table 5.1. Biotope area weighting factors

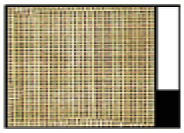
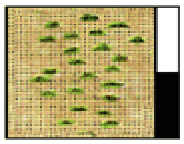
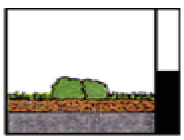
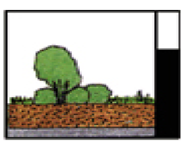
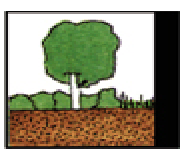
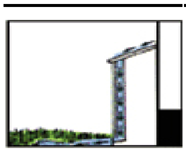
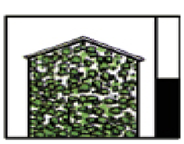
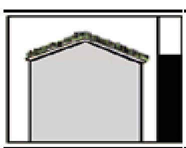
Weighting factor / per m² of surface type		Description of surface types
	Sealed surfaces **0.0**	Surface is impermeable to air and water and has no plant growth (e.g., concrete, asphalt, slabs with a solid subbase)
	Partially sealed surfaces **0.3**	Surface is permeable to water and air; as a rule, no plant growth (e.g., clinker brick, mosaic paving, slabs with a sand or gravel subbase)
	Semi-open surfaces **0.5**	Surface is permeable to water and air; infiltration; plant growth (e.g., gravel with grass coverage, wood-block paving, honeycomb brick with grass)
	Surfaces with vegetation, unconnected to soil below **0.5**	Surfaces with vegetation on cellar covers or underground garages with less than 80 cm of soil covering
	Surfaces with vegetation, unconnected to soil below **0.7**	Surfaces with vegetation that have no connection to soil below but with more than 80 cm of soil covering
	Surfaces with vegetation, connected to soil below **1.0**	Vegetation connected to soil below, available for development of flora and fauna
	Rainwater infiltration per m² of roof area **0.2**	Rainwater infiltration for replenishment of groundwater; infiltration over surfaces with existing vegetation
	Vertical greenery up to a maximum of 10 m in height **0.5**	Greenery covering walls and outer walls with no windows; the actual height, up to 10 m, is taken into account
	Greenery on rooftop **0.7**	Extensive and intensive coverage of rooftop with greenery

Table 5.2. Maximum floor area ratios (FAR) and green roof FAR bonuses for a property with 100% building coverage in Athens, GA

zoning key:	C-G	commercial-general
	C-D	commercial-downtown
	C-O	commercial-office
	C-N	commercial-neighborhood
	C-R	commercial-residential
	IN	industrial

Zoning class	C-G	C-D	C-O	C-N	C-R	IN
Current maximum FAR	1.5	5.0	.75	.75	.25	2.5
Bonus FAR with 100% green roof coverage	.6	2.0	.3	.3	.1	1.0
Total FAR with green roof FAR bonus	**2.1**	**7.0**	**1.05**	**1.05**	**.35**	**3.5**

CHAPTER 6

CONCLUSION

As urban areas continue to expand and human populations are concentrated in developed areas, there is an increasing need to study interactions between humans and their environment with particular attention paid to the unique attributes of human-dominated environments (Grimm et al, 2000). These studies are necessarily interdisciplinary as aspects of both the natural and social sciences inform urban management decisions. New conceptual models build from empirical research performed in each of the relevant disciplines to create integrated frameworks for understanding urban ecosystems (Pickett and Cadenasso, 2006).

Using Alberti et al's (2003) model for testing changes in human-dominated urban ecosystems, this study focused on the relationship between the built environment, urban receiving water bodies, and the creation of environmentally functional space. The stormwater management capabilities of an extensive green roof system were evaluated in detail. A number of green roof stormwater management functions were documented from this evaluation. This extensive green roof is capable of retaining over 90% of the rainfall from small storm events. In Georgia, these small storms comprise most of the rainfall events that occur annually, with total storm volumes being the key precipitation factor rather than storm intensity. The green roof not only retained stormwater, but delayed the peak runoff rates from the rooftop as the stormwater abstraction occurs at the onset of rainfall when the growing media reaches saturation. After this point the runoff hydrograph reflected that of a gravel roof. The hydrologic results allowed a curve number value of 86 to be generated as a modeling tool for extensive green roof systems.

Using the Tanyard Branch watershed as a case study, spatial analysis applied the green roof hydrologic results to a broader scale and included effects on the receiving water body. The reduction in the amount of total impervious area in the watershed was dramatic for downtown areas near the urban core. It was found that the scale of analysis is critical for prioritizing areas of the watershed which would benefit the most from green roof implementation. In this case, local zoning classifications were found to provide sufficient spatial disaggregation while not being overwhelmingly data intensive. Green roof storage across the watershed was sufficient to mimic the predevelopment abstraction from urban forests. At the parcel scale, initial abstraction values from hydrologic models were met when rooftops covered over 30% of the site. Using the curve number method for hydrologic modeling further illustrated the need for detailed spatial resolution at the zoning scale as 40% of the 1.27 cm storm event was retained when flat roofs were greened in the commercial downtown zone as compared to a 19% reduction at the watershed scale. Stormwater volumes and watershed peak outflow rates were significantly reduced for small storm events using widespread green roof coverage.

Since humans are both the driving cause and solution to urban environmental problems, in chapters 4 and 5 economic motivations and policy initiatives were assessed. The cost-benefit analysis shows that under present market conditions, it is understandable why green roofs have not begun to be implemented on a large scale. The net present value of extensive green roof systems costs 12% more to society and 18% more to private interests than traditional roofing practices. Considering reasonable assumptions about the maturation of the green roof industry in this country decreases the premium $0.40 on every dollar resulting in cost savings when green roofs are installed. This sensitivity analysis justifies the use of public funds and policy incentives to encourage green roof implementation.

An evaluation of green roof policies allowed salient and successful features of the policies to be identified and a new model policy to be developed and applied in Athens, GA. A number of voluntary incentive programs including density bonuses and stormwater utility fee credits offer efficient and politically feasible alternatives to the establishment of a green roof technology standard. The public benefits provided by the green roofs, however, give policy makers an opportunity to create public demonstration projects and incorporate green roofing standards in the jurisdiction's existing green building policy.

The practice of extensive roof greening has been shown to have a profound effect at a variety of scales and for a variety of purposes in the urban environment. This study focused primarily on the hydrologic impacts of green roof systems and the consequential stormwater management opportunities provided by the practice. Green roofs were found to be an important stormwater management tool particularly in highly developed areas of a watershed for small storm events. The feasibility of retrofitting extensive green roof systems into the existing urban landscape also allows for environmental mitigation to be performed in areas where this may have been previously been economically impractical. This work integrates the different disciplines of ecology, hydrology, engineering, economics, and environmental policy into a cohesive analysis critical to understanding how future cities may be made more ecologically benign. Using innovative practices such as green roofs may not entirely remove the imprint of humanity on natural systems, but they do provide ecosystem services in the urban landscape that may allow for a levels of sustainability not yet achieved in human-dominated ecosystems.

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APPENDIX A

REGRESSION METHOD TO ESTIMATE MAXIMUM SOIL MOISTURE STORAGE

A regression method was used to estimate the maximum soil moisture storage by solving for S:

$$S = \frac{P_e}{Q}\left(P_e - Q\right) \tag{A1}$$

which is equivalent to:

$$S = \frac{\left(P - I_a\right)}{Q}\ \left[\left(P - I_a\right) - Q\right] \tag{A2}$$

and

$$S = \frac{\left(P - \alpha S\right)}{Q}\ \left[\left(P - \alpha S\right) - Q\right] \tag{A3}$$

This equation can be re-written as:

$$S\,Q = P^2 - P\,Q - 2\,\alpha\,P\,S + \alpha\,S\,Q + \left(\alpha\,S\right)^2 \tag{A4}$$

which is the same as:

$$\left(\alpha\,S\right)^2 + \left(\alpha\,Q - Q - 2\,\alpha\,P\right)S + \left(P^2 - P\,Q\right) = 0 \tag{A5}$$

This can be written as the quadratic equation:

$$a\,S^2 + b\,S + c = 0 \tag{A6}$$

where the coefficients, a, b, and c are known, and given by:

$$a = \alpha^2 \tag{A7}$$

$$b = \alpha\,Q - Q - 2\,\alpha\,P \tag{A8}$$

$$c = P^2 - P\,Q \qquad \text{(A9)}$$

The quadratic equation can be solved for the unknown storage, S, using the regression equation $y = S\,x$, where:

$$y = c + a\,S_i^2 = P\,(P - Q) + (\alpha\,S_i)^2 \qquad \text{(A10)}$$

and

$$x = -b = 2\,\alpha\,P + (1 - \alpha)\,Q \qquad \text{(A11)}$$

and where an initial value of the maximum storage, S_i, is iterated until a stable estimate is achieved.

APPENDIX B

TOTAL IMPERVIOUS AREA AND ROOFTOP IMPERVIOUS AREA AT FOUR SPATIAL SCALES

				% TIA	% RIA	% flat roof of RIA
Tanyard Branch Watershed				53.80	15.88	46.97
Subwatershed	1			54.91	16.43	48.02
	2			52.17	12.95	22.29
	3			59.42	16.47	89.91
	4			56.24	16.65	65.02
	5			47.26	14.74	20.41
Zoning	government (university)			58.75	15.80	73.66
	commercial downtown			77.11	23.28	85.53
		Parcel	1	92.31	23.01	100
			2	90.38	82.84	100
			3	84.47	0	0
			4	69.93	2.73	0
			5	63.19	10.11	100
	commercial general			69.24	14.92	66.57
			1	54.08	21.68	100
			2	63.23	20.51	99.42
			3	86.79	61.54	0
			4	22.14	10.85	0
			5	39.00	9.51	0
	commercial office			54.12	14.69	25.27
			1	59.30	37.01	0
			2	29.01	23.68	0
			3	17.20	5.87	0
			4	32.15	13.94	0
			5	58.77	21.65	.78
	mixed density residential (16 units/0.4 ha)			45.21	15.63	8.38
			1	52.10	0	0
			2	41.76	39.23	0
			3	25.09	0	0
			4	54.01	21.86	0
			5	33.04	24.48	0
	mixed density residential (24 units/0.4 ha)			40.32	13.34	3.36
			1	31.52	0	0
			2	25.14	22.47	0
			3	11.24	0	0
			4	33.76	15.88	0
			5	0	0	0
	single family residential (6 units/0.4 ha)			37.79	18.36	0
			1	36.15	22.48	0
			2	20.70	14.29	0
			3	33.87	26.20	0
			4	44.06	24.82	0
			5	22.16	9.86	0
	single family residential (4 units/0.4 ha)			35.19	14.59	1.10
			1	30.03	23.63	0
			2	29.92	14.96	0
			3	20.92	17.06	0
			4	29.61	21.98	0
			5	21.96	21.62	0

APPENDIX C

CURVE NUMBERS (CN) FOR THREE SCENARIOS AT FOUR SPATIAL SCALES

			Existing composite CN	All green roofs CN	All flat green roofs CN
Tanyard Branch Watershed			92	90	91
Subwatershed	1		92	90	91
	2		91	90	91
	3		93	91	91
	4		93	91	92
	5		91	89	90
Zoning	government (university)		93	91	92
	commercial downtown		95	92	92
	Parcel	1	97	94	94
		2	97	87	87
		3	96	96	96
		4	94	93	94
		5	93	92	92
	commercial general		94	92	93
		1	92	89	89
		2	93	90	90
		3	96	89	96
		4	87	86	87
		5	89	88	89
	commercial office		92	90	91
		1	92	88	92
		2	88	85	88
		3	86	86	86
		4	89	87	89
		5	92	90	92
	mixed density residential (16 units/0.4 ha)		90	88	90
		1	91	91	91
		2	90	85	90
		3	88	88	88
		4	92	89	92
		5	89	86	89
	mixed density residential (24 units/0.4 ha)		90	88	90
		1	88	88	88
		2	88	85	88
		3	86	86	86
		4	89	87	89
		5	84	84	84
	single family residential (6 units/0.4 ha)		89	87	89
		1	89	86	89
		2	87	85	87
		3	89	86	89
		4	90	87	90
		5	87	86	87
	single family residential (4 units/0.4 ha)		89	87	89
		1	88	85	88
		2	88	86	88
		3	87	85	87
		4	88	86	88
		5	87	84	87

APPENDIX D

GREEN ROOF STORMWATER BEST MANAGEMENT PRACTICE (BMP)

3.3.10 VEGETATED (GREEN) ROOFS

Limited Application
Structural Stormwater Control

Description: Vegetated roofs typically contain layers engineered growing media and drainage materials which are incorporated into a roof membrane and support plant communities which are tolerant of the extreme weather conditions found on rooftops.

KEY CONSIDERATIONS

DESIGN CRITERIA:

- Thin-layered, or extensive, green roof systems (2-6") are recommended and most cost-effective
- Growing media should be an engineered mix of less than 10% organic matter
- The roof's waterproofing membrane must be protected from root penetration
- Irrigation and fertilization are not necessary once most extensive green roof systems are established

ADVANTAGES / BENEFITS:

- No land costs in highly urbanized areas
- Highly effective stormwater retention for small storm events
- Easily retrofitted on existing buildings

DISADVANTAGES / LIMITATIONS:

- Difficult on roofs with pitches greater than 2:12
- Roofs costs approximately twice as much as a traditional roof
- Few experienced installers or green roof examples

MAINTENANCE REQUIREMENTS:

- Semiannual inspection and maintenance similar to traditional roofs

POLLUTANT REMOVAL

80%	**Total Suspended Solids**
0%	**Nutrients** - Total Phosphorus / Total Nitrogen removal
50%	**Metals** - Cadmium, Copper, Lead, and Zinc removal
N/A	**Pathogens** - Coliform, Streptococci, E.Coli removal

STORMWATER MANAGEMENT SUITABILITY

- [x] **Water Quality**
- [x] **Channel Protection**
- [ ] **Overbank Flood Protection**
- [ ] **Extreme Flood Protection**

Accepts Hotspot Runoff: *No*

FEASIBILITY CONSIDERATIONS

L	**Land Requirement**
M-H	**Capital Cost**
L	**Maintenance Burden**

Residential Subdivision Use: *No*

High Density/Ultra-Urban: *Yes*

Drainage Area: *n/a*

Soils: *n/a*

Other Considerations:

- *A*
- *B*
- *C*
- *D*

3.3.10.1 General Description

Green roofs have been used for decades in Europe as a stormwater management tool and urban greenspace provider. Many of the current green roof systems utilize German technology and materials. Two general categories of green roof systems exist. Extensive systems are characterized by their thin (2-6”) growing media profile, limited plant palate, and low maintenance and installation costs ($8 - $14/sf). Intensive systems contain a deeper (>6”) substrate layer, can have a wide range of plants and may cost greater than $50/sf. This BMP is designed for extensive green roof systems as they provide the most cost-effective environmental benefit.

Extensive green roofs are engineered stormwater storage areas which typically contain a layered system of roofing. As discussed below, some modular systems do not use a layered approach. The layers are designed to retain water for plant uptake while not creating ponding of water on the roof surface. The primary emphasis in design is for the water to drain vertically through the media and then run horizontally along the waterproofing layer towards the outlet. These types of green roofs are designed to have minimal maintenance and upkeep. Depending on the plants selected, after an establishment period the roof should not need irrigation or fertilization. These activities are not recommended for extensive green roofs as they may reduce the water holding capacity of the growing media and potentially affect water quality draining the green roof.

Flexibility in design is typically limited by the structural capacity of the roof system and the budget constraints of the installer. The deeper the growing media, the heavier the saturated weight of the roof system and the more likely the need for structural reinforcement. A system with 3” of growing media has a live load of approximately 24 lbs/ft^2. The total amount of live load can be calculated based on the media’s water holding capacity.

<u>2 Types of extensive green roof systems</u>

1) Incorporated green roof

The most common type of extensive green roof is one that is directly incorporated into the building envelope. A number of manufacturers market a single source extensive system that can contains all the components necessary for a complete installation (Figure 3.3.10-1). This often involves a series of layers above the roof deck including:

- waterproofing

  The waterproofing layer is critical to the success of any roof, whether green or not. Many manufacturers will recommend premium waterproofing materials such as PVC, modified bitumen, rubberized asphalt for extensive green roof systems. While there often is a longer warranty associated with these types of waterproofing layers, a properly designed green roof should serve to protect the existing waterproofing rather than cause additional damage. In fact, many green roof proponents claim the protection from ultra-violet radiation, physical damage and temperature fluctuation serves to extend the waterproofing life over twice as much as without the green roof.

  Care should be taken during green roof installation that the waterproofing layer is not damaged as once the system is installed, repair and detection are difficult.

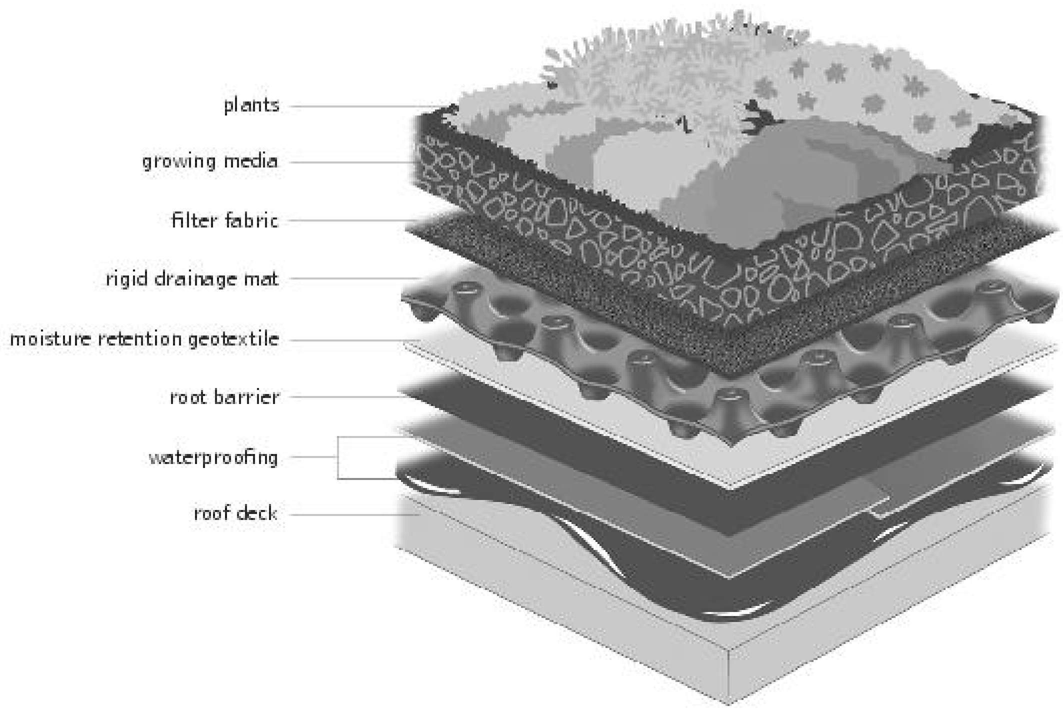

Figure 3.3.10-1. Typical cross-section from an extensive green roof

- root barrier

  An essential layer of the green roof system is the root barrier. This layer protects the waterproofing from degradation and penetration by the plant's root system. Some waterproofing layers such as PVC and EPDM inherently are impenetrable to root intrusion and therefore an additional layer is not needed. Waterproofing layers are commonly made from bituminous materials which are susceptible to failure from root penetrations. In these cases, an impassable layer must be installed which will inhibit root passage. A minimum of 30 mil thermoplastic sheeting should be used.

- drainage

  Modern green roofs need to be well drained to maintain favorable growing conditions for the plants. Extensive green roof growing media typically has a high degree of hydraulic conductivity and this may preclude the need for a drainage layer. Often, however the drainage layer is multi-functional in that it provides additional stormwater storage capacity while allowing for air circulation.

  The drainage layer may be comprised of synthetic drainage matting and sheets or aggregate with large void spaces. Drainage layers must be designed to connect directly with the roof's outlet structure. Synthetic drainage material is designed to be lightweight, maintain its structural integrity, and prevent anoxic conditions from developing. Some of these layers use an "egg crate" design where the cups retain additional water for the plants while the ridges allow for air circulation (Figure 3.3.10-7). Other systems incorporate a rigid woven plastic which has a thinner profile than the egg crate systems.

  Aggregate materials used for drainage are coarse and lightweight. The advantage of using aggregate as a drainage layer is that, depending on the needs of the plants, the root zone can be extended as deep as needed, whereas in the synthetic drainage mats, there is one root depth available. The disadvantage is the weight tradeoff. Aggregate material commonly used in this layer is expanded clay, slate, or shale.

- geotextile media separation

  Separation between the growing media and drainage materials is important to prevent fines in the media layer to clog the drainage layer. The use of a geotextile in the form of nonwoven fabric is recommended. The separation layer may allow for roots to penetrate into the drainage course which is particularly important for extensive green roofs during drought conditions. Separation fabric must also resist breakdown over time. Some of the separation fabrics come directly attached to the synthetic drainage mats as the sheets come in an integrated system.

- engineered growing media

  Possibly the most important layer as well as the most highly specified in extensive green roof systems is the growing media. The media layer serves the functions of providing nutrient and physical support for the plants, remaining lightweight to reduce roof loads, allowing for free drainage of water after storm events, retaining stormwater and using natural filtration to improve water quality.

  The multi-functional components of this layer leads to optimal mixes largely dependent on the goals of the project. For stormwater control, the most important feature is to maximize rainfall retention properties of the media during rainfall events while allowing the media to drain completely and stay lightweight during inter-event periods. Many single-source proprietary mixes are available. For water quality purposes, mineral aggregates should compose > 90% of the media mix with organic matter comprising less than 5% of the media. Water storage capacity should be > 20% by volume for extensive systems.

- plant material

  Plant selection is relatively limited on extensive green roofs as the depth of growing media only allows plants to thrive that are well-adapted to the harsh conditions of a rooftop. Many varieties of Sedum species fit this specification. Species lists are dependent on the zone. Native plant species may be used, however experience has shown that over time Sedums will overtake many of the native species.

2) Modular systems

Recent green roof technology development has focused on developing modular systems that can be easily installed and transported without direct incorporation of the green roof into the building envelope (Figure 3.3.10-2). The modular systems are effectively thin-layer trays that may be made out of heavy plastic or aluminum with drainage holes in the bottom. These types of extentive systems do not disturb the waterproofing layer and are easily removed for maintenance and repairs. Their unit costs are, on average, more than incorporated systems. While few modular systems contain the specialized layers found in incorporated systems, the growing media and plant materials are similar.

Figure 3.3.10-2. Modular extensive green roof

3.3.10.2 Stormwater Management Suitability

Extensive green roofs perform very well at reducing stormwater quantities from small storm events. The roofs serve to add stormwater storage in areas lacking this service. The majority of this retention is experienced during the initial onset of rainfall as the media and water retention layers reach field capacity. This period of initial abstraction can be determined from the retention capacity of the soil which can then be incorporated into stormwater modeling methods

Water Quality

The ability of green roofs to improve water quality is not readily apparent. Much of the pollution to stormwater results from the transportation network which does not affect roof surfaces. Roof runoff pollution sources include heavy metals leaching from roof materials, dry deposition, and poor rainfall water quality. Industry sources assume a level of water quality improvement from green roofs that is unfounded in the scientific literature. The high porosity and relatively large abundance of nutrients in the growing media relative to a conventional roof often times results in runoff from green roofs containing elevated dissolved nutrient levels with a slight reduction in certain heavy metals. Media mixes with low amounts of organic matter (2-5%) are highly encouraged for water quality purposes. Fertilization should be eliminated after plant establishment period.

Channel Protection

Extensive green roofs can capture a large portion of the channel protection volume Cp_v, depending on the amount of rooftop relative to the site area. Since retention only occurs on the rainfall that lands on the roof, the volume amount is limited to the area of the rooftop and the depth of storage. For sites with a proportionately small amount of impervious surface as rooftop, other structural controls should be provided to manage the Cp_v extended detention.

Overbank Flood Protection

Other management measures should be used in conjunction with an extensive green roof to reduce the post-development peak flow of the 25-year storm (Q_p) to pre-development levels (detention).

Extreme Flood Protection

Extensive green roofs will naturally overflow when saturated so no overflow protection devices are needed for extreme storm flows. They do not function well to retain significant amounts of stormwater from large storm events like the 100-year storm.

3.3.10.3 Pollutant Removal Capabilities

Depending on the media mix, extensive green roofs can either remove significant amounts of pollutants or contribute large amounts of dissolved nutrients to runoff. Green roofs are assumed to perform like infiltration BMPs and therefore the TSS goal of 80% is assumed to be achieved. This goal has been established as a surrogate for other water quality parameters, such as nutrient reductions, and this may be misleading for green roof systems as the amount of nutrient loading is dependent upon the growing media mix and may be highly variable.

3.3.10.4 Application and Site Feasibility Criteria

General Feasibility

- Suitable for Residential Subdivision Usage - NO
- Suitable for High Density/Ultra Urban Areas - YES
- Regional Stormwater Control - NO

Physical Feasibility - Physical Constraints at Project Site

- Drainage Area – only constrained by size of the roof
- Space Required – no additional space needed beyond the rooftop
- Site Slope – recommended for flat roofs (2-8%)

3.3.10.5 Planning and Design Criteria

*The following criteria are to be considered **minimum** standards for the design of an extensive green roof facility. Consult with the local review authority to determine if there are any variations to these criteria or additional standards that must be followed.*

A. LOCATION AND SITING

- To maximize the stormwater retention performance of green roof systems, this BMP should be installed on relatively flat rooftops. Rooftops with a pitch greater than 1:12 are not recommended for roof greening as performance standards have not been extensively tested for sloped roofs

- Roof drains must drain freely as standing water may compromise the performance of the roof system.

- The structural capacity of the roof must be verified by a structural engineer before green roof construction commences.

- Roof waterproofing should be new or in excellent condition with provisions included during installation to protect the waterproofing from damage

- The roof must be accessible for green roof installation and maintenance purposes. In certain areas this may involve the use of cranes to lift the material to the rooftop and/or permission to block off sections of street.

B. GENERAL DESIGN

- A well designed incorporated extensive green roof consists of:

  1) vegetation selected for growth potential based on the plant hardiness zone
  2) growing media with composed primarily of inorganic mineral substrate
  3) drainage layers, either composed of synthetic material or inorganic substrate
  4) root barrier protection

- Outlet structures, roof penetrations, and roof edges should contain at least 12 inches of nonvegetated and non-growing media area as a buffer from the active green roof section. Roof flashings should extend beyond the vegetated layer at least six inches.

- Extensive green roofs should be designed for the stormwater to drain vertically through the plant material and growing media, then horizontally to the roof outlet as would normally occur on a typical rooftop.

- Amount of stormwater storage in the extensive green roof can be designed based on the water holding capacity of the growing media.

- It is strongly recommended on extensive systems with < 4” of growing media to specify synthetic moisture retention layers or “egg crate” drainage mats to ensure plant survival during periods of low precipitation. Alternatively, supplemental irrigation or watering capability should be ensured during these times.

- Plant selection should be largely based on the recommendations by a green roof horticulturalist. Georgia falls in zones 7 & 8 with a wide variety of plants available for selection. The extreme nature of the rooftop limits plant usage to those well-adapted to low nutrient and water conditions and extreme temperature fluctuations.

- Vegetation substrate mixes should not compact over time. Settling should not occur for more than 10% of the original depth of the media course.
- A vegetation free zone should exist 12" from all roof edges and roof penetrations.

See figures 3.3.10-3 – 3.3.10-5 for various types of green roof cross-sections. Figure 3.3.10-6 illustrates a typical edge profile. Figure 3.3.10-7 details "egg-crate drainage materials.

C. PHYSICAL SPECIFICATIONS / GEOMETRY

- Green roof physical specifications are determined by the roof shape and size.
- Depth of engineered growing media may vary from 2-6 inches depending on the stormwater management goals and structural capacity of the roof.
- The roof slope should be relatively flat (~2%) to ensure maximum retention and avoid the need for media stabilization.
- Water should be allowed to freely drain through the roof outlet and not pond on the surface of the growing media and vegetation.

E. OUTLET STRUCTURES

- Roof outlets may be tied into the main storm sewer system or routed through additional BMPs in the treatment train.
- Outlets must be clear from debris and be accessible in the case of stoppages below the outlet

G. MAINTENANCE ACCESS

- The roof should be accessible only for biannual maintenance and inspections. Extensive systems are typically not designed for extended periods of direct human interaction due to weight constraints.

H. SAFETY FEATURES

- Safety features are what would commonly be found on any roof system

I. LANDSCAPING

- Extensive green roofs use plant material that has significant horizontal coverage to maximize shading, moisture retention and lower the plant establishment period.
- Plants should be able to tolerate extreme temperature conditions of the rooftop, limited soil water and nutrients, and extended periods of low soil moisture
- Complete plant lists can be found from a horticulturalist specializing in green roof plants.

3.3.10.6 Design Procedures

Step 1. Compute runoff control volumes from the Unified Stormwater Sizing Criteria

Calculate the Water Quality Volume (WQ_v), Channel Protection Volume (Cp_v), Overbank Flood Protection Volume (Q_p), and the Extreme Flood Volume (Q_t)

Details on the Unified Stormwater Sizing Criteria are found in Section 1.4 of the GSMM

Step 2. Determine if the development conditions are appropriate for the use of a green roof

Consider the Planning and Design Criteria in 3.3.10.5 (Location and Siting)

Step 3. Determine amount of stormwater that may be stored in the green roof

To determine the specific stormwater storage capacity of green roof systems, key physical properties of the plants, growing media and moisture retention layers need to be known. This makes general formula difficult to apply. These properties include:

- Maximum water retention of the media and other green roof layers
- Porosity of media
- Hydraulic conductivity of media
- Leaf area index

Generally, extensive green roofs never reach saturation because the hydraulic conductivity of the media is extremely high for extensive applications. The storage in these systems is essentially limited to the field capacity of the media layer and any additional water held in the synthetic green roof layers. Consultation with the media provider and green roof manufacturer allows for storage calculation to be performed.

A simplified formula may be used in stormwater management calculations:

$$FC_{media} + MR_{syn} = GR_v$$

where:

FC_{med} = field capacity of the growing media
MR_{syn} = moisture retention of the synthetic green roof materials
GR_v = additional stormwater water storage volume provided by green roof

Step 3. If stormwater management goals are not met with stormwater storage of the green roof investigate additional BMPs

Incorporate stormwater management BMPs such as bioretention areas that will allow stormwater control volumes to be managed while minimizing centralized infrastructure costs.

3.3.10.7 Inspection and Maintenance Requirements

Table 3.3.10-1 Typical Maintenance Activities for Green roofs

Activity	Schedule
• Inspect roof surface for unwanted vegetation and remove as needed • Inspect roof drain for clogs or material that may be blocking the outlet	Semiannual Inspection
• Irrigation and routine care typical of any planted area	During establishment

Additional Maintenance Considerations and Requirements

- Maintenance requirements are largely determined by the plants selected and the complexity of the roof system. The hardier plants recommended for green roofs will need little maintenance and are often self-maintaining once established.

3.3.10.8 Example Green Roof schematics

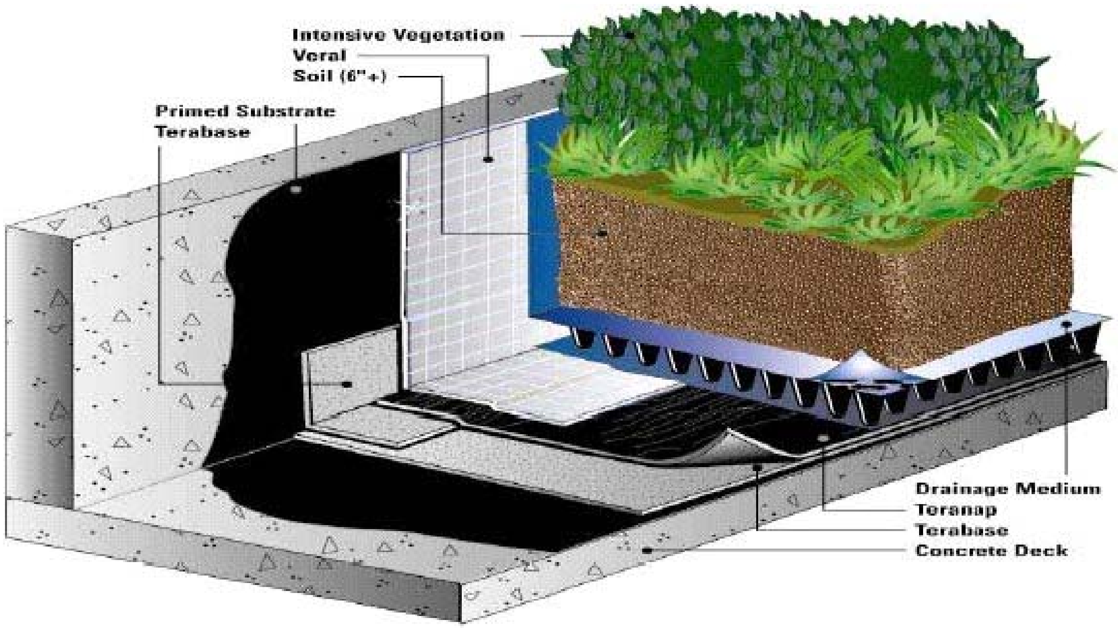

Figure 3.3.10-3 Green roof cross-section (Source: www.cif.org)

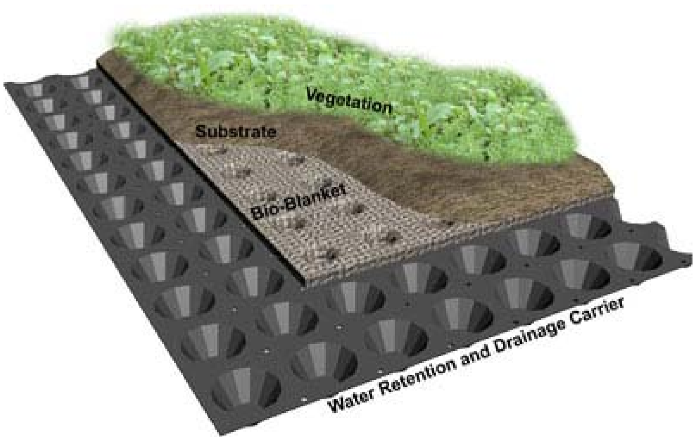

Figure 3.3.10-4 Green roof cross-section (Source: Elevated Landscape Technologies)

Figure 3.3.10-5 Green roof cross-section (Source: www.epa.gov/greeningepa/ facilities/boston-hq.htm.)

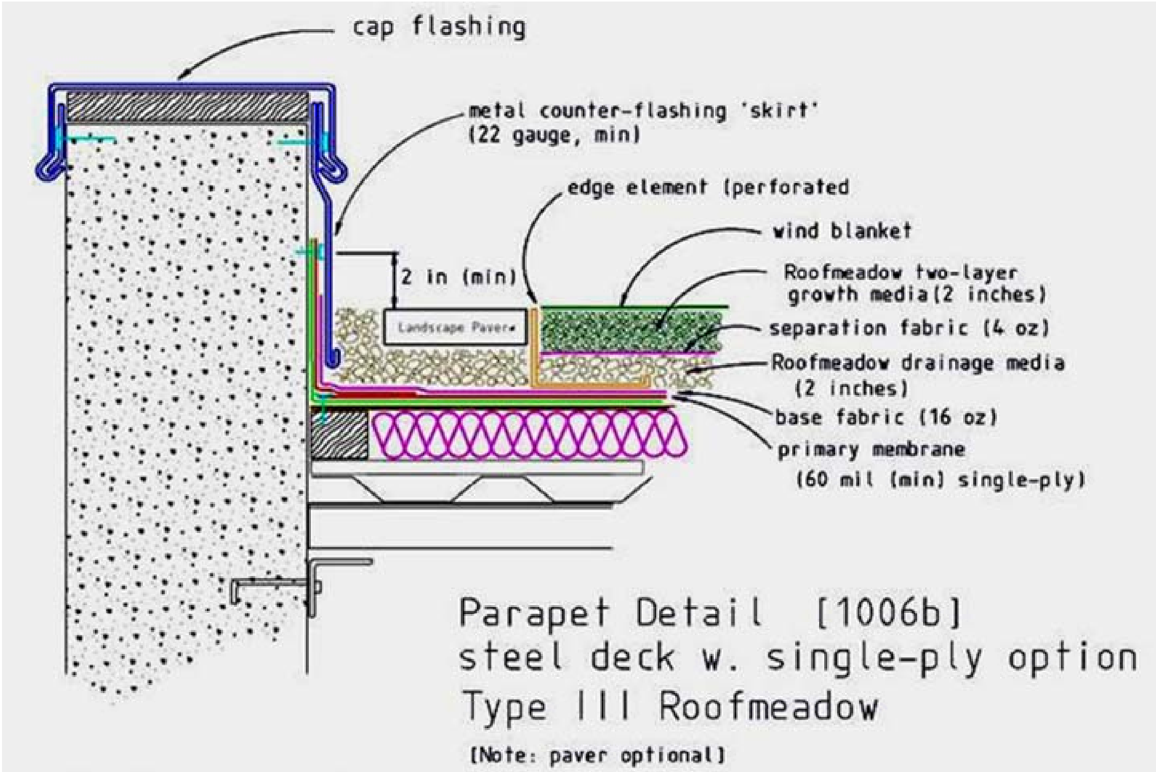

Figure 3.3.10-6 Typical green roof edge detail (Source: Roofscapes, Inc)

Figure 3.3.10-7 Synthetic "egg-crate" drainage material (Source: Roofscapes, Inc)

APPENDIX E

WATER QUALITY FROM RAINFALL AND ROOF RUNOFF (GREEN & BLACK)

All constituent concentrations in mg/l											
Date	time	rainfall (in)	sample	TN	TP	Hardness	pH	Al	B	Ca	Cd
6-Oct	9:00	1.59	Rain	0.549	0	0.88	6.15	0.1218	<.01	0.353	<.005
6-Oct	9:00	1.59	Black	0.323	0.007	1.92	5.48	<.025	<.01	0.6581	<.005
6-Oct	9:00	1.59	Green	1.997	0.941	66.39	6.33	0.1091	0.0231	21.83	<.005
11/20/2005	21:17	1.01	Rain	1.102	0.002	2.32	5.13	0.2377	<.01	0.801	<.005
11/20/2005	21:17	1.01	Black	4.043	0.017	19.6	4.62	0.3075	0.0245	6.885	<.005
11/20/2005	21:17	1.01	Green	5.156	1.177	57.68	7.13	0.0384	0.029	18.5	<.005
12/4/2005	23:00	1.7	Rain	0.742	0	1.12	5.2	0.2015	<.01	0.3518	<.005
12/4/2005	23:00	1.7	Black	0.62	0.006	4.08	4.79	0.0411	<.01	1.368	<.005
12/4/2005	23:00	1.7	Green	1.484	0.546	36.71	6.61	<.025	0.0156	12.09	<.005
12/15/2005	1:00	0.1	Rain	0.652	0	0.69	4.61	0.1702	0.0104	0.186	<.005
12/15/2005	1:00	0.1	Black	1.182	0.001	5.34	4.85	0.0581	0.0171	1.79	<.005
12/15/2005	1:00	0.1	Green	1.116	0.444	23.79	6.93	<.025	0.0159	7.795	<.005
1/12/2006	7:47	0.33	Rain	0.967	0	2.8	5.62	0.2659	<.01	0.7351	<.005
1/12/2006	7:47	0.33	Black	1.038	0	4.62	5.17	0.1016	<.01	1.498	<.005
1/12/2006	7:47	0.33	Green	1.153	0.496	21.12	6.97	0.0602	<.01	6.956	<.005
1/23/2006	10:07	0.17	Rain	1.272	0	1.42	5.27	0.5335	<.01	0.388	<.005
1/23/2006	10:07	0.17	Black	0.347	0.003	3.38	5.93	0.0628	0.0245	1.119	<.005
1/23/2006	10:07	0.17	Green	1.748	0.368	23.39	6.75	0.0605	0.0123	7.668	<.005
2/7/2006		1.28	Rain	0.663	0.004	2.09	5.75	0.0285	<.01	0.8379	<.005
2/7/2006		1.28	Black	0.51	0	6.36	5.14	<.025	<.01	2.333	<.005
2/7/2006		1.28	Green	1.302	0.377	21.08	7.13	<.025	<.01	7.069	<.005
4/1/2006	7:24	0.1	Rain	2.503	0.08	3.36		0.4741	<.01	1.128	<.005
4/1/2006	7:24	0.1	Black	3	0.006	16.67		0.2132	0.0297	5.666	<.005
4/1/2006	7:24	0.1	Green	1.232	0.266	20.07		<.025	0.0247	6.371	<.005
4/8/2006	5:18	0.18	Rain	1.053	0.353	1.51		0.0313	<.01	0.475	<.005
4/8/2006	5:18	0.18	Black								
4/8/2006	5:18	0.18	Green	1.282	0.256	20.41		<.025	<.01	6.55	<.005
5/4/2006	14:40	0.5	Rain			1.35		0.2075	<.01	0.4243	<.005
5/4/2006	14:40	0.5	Black			14.06		0.1914	0.0131	4.87	<.005
5/4/2006	14:40	0.5	Green			23.72		<.025	0.0174	7.331	<.005

All constituent concentrations in mg/l											
Date	time	rainfall (in)	sample	Cr	Cu	Fe	K	Mg	Mn	Mo	Na
6-Oct	9:00	1.59	Rain	<.005	<.005	<.005	<.4	<.015	<.005	<.005	0.233
6-Oct	9:00	1.59	Black	<.005	<.005	0.1272	<.4	0.0675	0.0092	<.005	0.306
6-Oct	9:00	1.59	Green	<.005	0.0144	0.4571	16	2.923	0.092	<.005	3.341
11/20/2005	21:17	1.01	Rain	<.005	<.005	0.0167	<.4	0.079	0.0071	<.005	0.399
11/20/2005	21:17	1.01	Black	<.005	0.0085	0.8279	0.96	0.5977	0.1259	<.005	0.969
11/20/2005	21:17	1.01	Green	<.005	0.0156	0.425	20.8	2.823	0.0179	<.005	2.314
12/4/2005	23:00	1.7	Rain	<.005	<.005	0.0077	<.4	0.059	<.005	<.005	0.149
12/4/2005	23:00	1.7	Black	<.005	0.0131	0.1455	<.4	0.1636	0.0273	<.005	0.42
12/4/2005	23:00	1.7	Green	<.005	0.0148	0.0759	12.9	1.606	<.005	<.005	1.518
12/15/2005	1:00	0.1	Rain	<.005	<.005	0.0209	<.4	0.0555	<.005	0.0066	0.375
12/15/2005	1:00	0.1	Black	<.005	0.0151	0.1713	<.4	0.2137	0.0311	0.0132	0.56
12/15/2005	1:00	0.1	Green	<.005	0.0095	0.1197	9.29	1.065	<.005	0.0099	0.901
1/12/2006	7:47	0.33	Rain	<.005	<.005	0.0328	<.2	0.2367	<.005	<.005	1.281
1/12/2006	7:47	0.33	Black	<.005	<.005	0.0924	<.2	0.217	0.0259	<.005	1.063
1/12/2006	7:47	0.33	Green	<.005	0.0309	0.0992	6.25	0.9232	<.005	<.005	1.035
1/23/2006	10:07	0.17	Rain	<.005	0.0067	0.0227	<.2	0.1096	<.005	<.005	0.665
1/23/2006	10:07	0.17	Black	0.0234	0.3238	0.0893	<.2	0.1443	0.0166	0.0228	0.38
1/23/2006	10:07	0.17	Green	<.005	0.0187	0.0777	5.38	1.045	<.005	0.0076	0.977
2/7/2006		1.28	Rain	<.005	<.005	<.005	<.4	<.015	<.005	<.005	<.005
2/7/2006		1.28	Black	<.005	<.005	0.1062	<.4	0.1342	<.005	<.005	0.377
2/7/2006		1.28	Green	<.005	0.0399	0.0219	4.3	0.8441	<.005	<.005	0.94
4/1/2006		0.1	Rain	<.005	0.0364	0.0493	0.49	0.1349	0.0111	<.005	0.565
4/1/2006		0.1	Black	<.005	0.0116	0.2817	0.76	0.6226	0.1082	<.005	1.633
4/1/2006		0.1	Green	<.005	0.0162	0.0545	2.31	1.023	<.005	0.0139	1.303
4/8/2006		0.18	Rain	<.005	0.0181	0.0094	0.26	0.08	<.005	<.005	0.422
4/8/2006		0.18	Black								
4/8/2006		0.18	Green	<.005	0.1051	0.0442	2.27	0.9952	<.005	<.005	1.192
5/4/2006		0.5	Rain	<.005	0.0106	0.0315	<.4	0.0717	0.0103	<.005	0.221
5/4/2006		0.5	Black	<.005	0.0166	0.665	0.57	0.4708	0.076	<.005	0.811
5/4/2006		0.5	Green	<.005	0.0782	0.059	3.08	1.329	<.005	<.005	1.272

All constituent concentrations in mg/l							
Date	time	rainfall (in)	sample	Ni	P	Si	Zn
6-Oct	9:00	1.59	Rain	0.0103	<.06	0.0518	0.01
6-Oct	9:00	1.59	Black	0.0103	<.06	0.1192	0.02
6-Oct	9:00	1.59	Green	<.01	1.051	3.857	0.05
11/20/2005	21:17	1.01	Rain	<.01	<.06	0.0294	0.04
11/20/2005	21:17	1.01	Black	<.01	<.06	0.2965	0.14
11/20/2005	21:17	1.01	Green	<.01	0.9864	4.88	0.03
12/4/2005	23:00	1.7	Rain	<.01	<.06	<.01	0.02
12/4/2005	23:00	1.7	Black	0.0118	0.0614	0.1823	0.05
12/4/2005	23:00	1.7	Green	0.0212	0.5439	5.021	0.03
12/15/2005	1:00	0.1	Rain	<.01	<.06	0.0218	0.02
12/15/2005	1:00	0.1	Black	<.01	<.06	0.0974	0.06
12/15/2005	1:00	0.1	Green	<.01	0.4425	3.219	0.02
1/12/2006	7:47	0.33	Rain	<.01	<.06	0.0739	0.01
1/12/2006	7:47	0.33	Black	<.01	<.06	0.1556	0.04
1/12/2006	7:47	0.33	Green	<.01	0.5125	3.183	0.02
1/23/2006	10:07	0.17	Rain	<.01	<.06	0.037	0.02
1/23/2006	10:07	0.17	Black	<.01	<.06	0.1681	0.04
1/23/2006	10:07	0.17	Green	<.01	0.3311	4.393	0.02
2/7/2006		1.28	Rain	<.01	<.06	<.01	0.06
2/7/2006		1.28	Black	<.01	<.06	0.1127	0.01
2/7/2006		1.28	Green	<.01	0.2985	3.254	<.005
4/1/2006		0.1	Rain	<.01	<.06	0.0838	0.07
4/1/2006		0.1	Black	0.0215	<.06	0.4454	0.14
4/1/2006		0.1	Green	<.01	0.2447	3.143	0.03
4/8/2006		0.18	Rain	<.01	<.06	0.0566	0.02
4/8/2006		0.18	Black				
4/8/2006		0.18	Green	<.01	0.2695	3.353	0.05
5/4/2006		0.5	Rain	<.01	<.06	0.0327	0.02
5/4/2006		0.5	Black	<.01	0.064	0.3002	0.12
5/4/2006		0.5	Green	<.01	0.2682	3.73	0.07