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 the green roof’s 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 percent for small storms (< 2.54 cm) to slightly less than 50 percent for larger storms (> 7.62 cm). Runoff from the green roof was 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 used to estimate the green roof curve number, CN = 86. This information can be used in hydrologic models for developing stormwater mitigation programs.

(KEY TERMS: environmental impacts; urbanization; best management practices; stormwater 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 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 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 arming streambanks 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 a municipality’s storm sewer system. The resulting biotic community is frequently dominated by a few tolerant species of fish and macroinvertebrates that 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 (NPDES) permitting process, which authorizes the federal or state government to implement a stormwater discharge permitting system (Perry, 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 that includes structural and nonstructural stormwater controls. Nonstructural controls primarily encompass 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, although roofs may constitute a substantial fraction of the total ISC, particularly in highly urbanized watersheds where the ISC exceeds 50 percent. Vegetated roof cover, also called green roofs, provides 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 that can absorb and retain stormwater rather than quickly shedding it 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, 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) that reported stormwater retention performance for small test plots in central Michigan. Research in English language journals is weighted toward green roof energy budget studies (Del Barrio and Palomo, 1998; Niachou et al., 2001; Wong et al., 2003) 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, however, is published in German, and few translated reports are available.

Stormwater BMPs are often classified as infiltration, detention, or retention systems (USEPA, 1999). These systems are all designed to retain stormwater before eventually releasing it into the stream system either through ground water 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 effect 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 a protocol for testing and monitoring 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 (USEPA, 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, 84.689°W). This building is part of the Boyd Graduate Studies building and is located in the heart of the campus. The building is a single-story building with a green roof that covers approximately 4,000 square feet. The roof is designed to be lightweight, easily replicated, and cost efficient. A second goal of this study was to develop a protocol for testing and monitoring 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 (USEPA, 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.
87.375°W) on the University of Georgia (UGA) campus in Athens, Georgia. Athens is 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 13-month study period, November 2003 through November 2004, was slightly less than average at 107.9 cm (Figure 1). While most months were drier than normal, two months (November 2003 and September 2004) were substantially wetter 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 percent 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 that 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 that 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 by 8.2 m for a total of 42.64 m² (Figure 2). The control plot (black roof) was left in its original state. The control plot – similar to

Figure 1. Average and Study Period Monthly Precipitation Depths.

Figure 2. Green (left) and Black (right) Roof Stormwater Runoff Plots.
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 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 under the growing medium 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/m², and the water retention capacity of the synthetic drainage panel is approximately 4 l/m² (American Hydrotech Inc., 2002). The growing medium is a Lightweight Roof Garden mix provided by ItSaul Natural LLC. This soil mix is a blend of 55 percent Stalite expanded slate, 30 percent United States Golf Association sand, and 15 percent composted organic matter composed primarily of worm castings. This medium has a bulk density of 1.508 g/cm³, and the total porosity is 50.6 percent. 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 by 3.4 by 6.25 cm plugs, which were planted in the growing medium at a density of 50 plants/m².

Discharge Measurement

The original drains beneath the control and test plot sections were disconnected and rerouted through two 120 cm by 30 cm by 30 cm stainless steel weirs. These weirs were located in the building basement directly below the experimental plots (Figure 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

Figure 3. Detail of Green Roof Composition Used in the Study.
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 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,

$$q = CA\sqrt{2gh}$$  \hspace{1cm} (1)
where \( q \) is the weir discharge (\( \text{cm}^3/\text{s} \)), \( C \) is the dimensionless orifice coefficient, \( g = 9.87 \text{ m/s}^2 \) is the gravitational constant, \( h \) is the weir stage (\( \text{cm} \)), and \( A \) is the cross-sectional area of the weir orifice (\( \text{cm} \)). 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

\[
A = \begin{cases} 
\pi r^2 & \text{outlet flooded} \\
\beta r^2 & \text{outlet partially flooded} \\
0 & \text{outlet dry}
\end{cases}
\]

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 13-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 (USEPA, 2002). Storm peak discharges, \( q_p \) (\( \text{L/s} \)), 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,

\[
t_p = \frac{1}{P} \sum_{i=1}^{n} P_i t_i
\]

where \( P \) is the total storm precipitation depth (\( \text{cm} \)), \( n \) is the total number of time intervals in which precipitation was observed during the storm, \( P_i \) is the depth of precipitation during the interval (\( \text{cm} \)), and \( t_i \) is the observation time (\( \text{s} \)). The time-to-peak discharge centroid also was 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 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,

\[
Q = \frac{F}{P_e - S}
\]

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

The \( CN \) is commonly related to \( S \) using the equation

\[
CN = \frac{1000}{S + 10}
\]

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 Appendix A, 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 1). A typical rainfall-runoff response is illustrated in Figure 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 that of a 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 the green and black roofs looked more similar once the growing medium reached saturation.

Green roof stormwater retention ranged from 39 to 100 percent, with an average retention just under 78 percent (Figure 7). Nearly all of the storm events with precipitation depths smaller than 1.27 cm retained...
more than 90 percent of the incident precipitation. A storm on March 20, 2004, with 0.41 cm of precipitation retained 100 percent. The smallest retention, expressed as a percentage, occurred during a 5.38 cm storm event on November 19, 2003, when 39 percent 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 a deeper growing medium.

An inverse relationship exists between the depth of rainfall and the percent of the stormwater that is retained (Figure 8), with nearly 88 percent from small storms (< 2.54 cm) retained, more than 54 percent from medium storms (2.54 to 7.62 cm) retained, and nearly 48 percent from large storms (> 7.62 cm) 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 9 presents peak discharge data for the green roof and black roof plots as a function of precipitation

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth (cm)</th>
<th>GR Runoff</th>
<th>Time to Peak (min)</th>
<th>Peak Discharge (L/s)</th>
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<tr>
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<td>5.38</td>
<td>3.27</td>
<td>183.09</td>
<td>0.56</td>
</tr>
<tr>
<td>February 6, 2004</td>
<td>2.69</td>
<td>1.32</td>
<td>74.95</td>
<td>-44.90</td>
</tr>
<tr>
<td>February 12, 2004</td>
<td>2.92</td>
<td>1.55</td>
<td>84.65</td>
<td>-37.79</td>
</tr>
<tr>
<td>March 6, 2004</td>
<td>0.38</td>
<td>0.01</td>
<td>18.46</td>
<td>11.66</td>
</tr>
<tr>
<td>March 20, 2004</td>
<td>0.41</td>
<td>0.00</td>
<td>108.15</td>
<td>-</td>
</tr>
<tr>
<td>March 30, 2004</td>
<td>1.47</td>
<td>0.22</td>
<td>154.76</td>
<td>81.20</td>
</tr>
<tr>
<td>May 12, 2004</td>
<td>0.33</td>
<td>0.01</td>
<td>4.18</td>
<td>3.80</td>
</tr>
<tr>
<td>May 16, 2004</td>
<td>0.28</td>
<td>0.01</td>
<td>6.51</td>
<td>6.31</td>
</tr>
<tr>
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<td>0.58</td>
<td>0.04</td>
<td>14.82</td>
<td>8.71</td>
</tr>
<tr>
<td>May 31, 2004</td>
<td>1.45</td>
<td>0.55</td>
<td>32.84</td>
<td>24.62</td>
</tr>
<tr>
<td>June 9, 2004</td>
<td>5.97</td>
<td>2.36</td>
<td>13.62</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
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</tr>
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</tr>
<tr>
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<td>4.26</td>
<td>54.43</td>
<td>20.06</td>
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<td>10.54</td>
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<tr>
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</tr>
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<td>36.16</td>
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<td>-48.13</td>
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<td>November 21, 2004</td>
<td>0.84</td>
<td>0.10</td>
<td>105.02</td>
<td>81.10</td>
</tr>
</tbody>
</table>
depth. 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. 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 10 presents the scatterplot between precipitation depth and the ratio between peak discharges for the green roof and the black roof. The green roof peak runoff is less than the black roof in all but one case. The runoff ratio increases as the precipitation depth increases. This increased runoff ratio could be
attributed to increased water content within the soil medium, 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 not to 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 11 presents a histogram of time-to-peak differences between green roofs and black roofs. Note that green roofs’ runoff peaks are generally delayed relative to black roofs. Only two peaks on the green roof preceded black roof peaks, while most (57 percent) 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 of long duration. The median time-to-peak is shorter for the black roof, at 12.9 minutes, than for the green roof, at 23.1 minutes. 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 greater than black roof response times.

**Curve Number Determination**

Figure 12 presents the observed relationship between runoff depth, Q (cm), and precipitation depth, P (cm). Also plotted are the lines of equal CN. The average CN for these data is CN = 86, which was obtained by estimating the maximum depth of moisture storage, S = 4.27 cm, as shown in Figure 13 using the best-fit line to the data for each storm event. Other land coverages with similar CN include cultivated land without conservation treatment and pastureland 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 percent, which is consistent with the type of soil material used. The conventional CN approach assumes 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 the 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 m² test plots demands a monitoring system that allows flow through, not complete containment, of the runoff.

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 more than 90 years, and most modern green roofs are expected to last at least 50 years as the vegetation shields the roof deck from ultraviolet radiation, which breaks down the waterproofing material (Porsche and Kohler, 2003). Additional structural loading may be another deterrent when deciding on whether to install a green roof. When saturated, this study’s green roof system added approximately 118.06 kg/m², compared to gravel ballast, which weighs anywhere from 48.39 kg/m² to 96.77 kg/m² (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 found that using a control and experimental plot design was helpful to find 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 the 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 base flow (Dunne and Leopold, 1978). In highly urbanized environments, however, little of this rainfall infiltrates and returns to the stream slowly as base flow, as most of it 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 most stormwater retention occurs at the beginning of storms as the growing media absorb the initial rainfall until it reaches saturation, at which point the black and green roof hydrographs look more 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 a porous growing medium and a synthetic drainage mat and water retention fabric; this allows the medium to drain and water to run off 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 that 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. Where climates do not have such seasonal fluctuations, green and black roofs 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 predetermined level. This type of 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 consumed by humans, the flora and fauna on the roof surface are the only organisms directly using 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 intensive development in an area, as in a business park, industrial complex, or urban infill project, green roofs may effectively be used to keep the site's runoff hydrograph from becoming dominated by stormflow.

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 dataset 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 to be used as a stormwater retention tool. Innovative stormwater management techniques are attempting to recreate the predevelopment hydrograph by using a variety of tools rather than simply relying upon one retention pond or stormwater BMPs 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 examine the tools necessary to lessen the impact that altered hydrology has on receiving water bodies (Riley, 1998; Booth et al., 2004). One way to accomplish this is to reduce the amount of impervious surface found in the watershed. Green roofs can replace a surface typically seen as a contributor to stormwater problems and a cause of urban stream degradation. For architects, this provides a way for new structures to have stormwater management built 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.

APPENDIX A

A regression method was used to estimate the maximum soil moisture storage by solving for \( S \),

\[
S = \frac{P}{Q} (P_e - Q)
\]

which is equivalent to

\[
S = \frac{(P-I_a)}{Q} (P-I_a) - Q
\]

and

\[
S = \frac{P - \alpha S}{Q} (P - \alpha S) - Q
\]
This equation can be rewritten as

\[ S Q = P^2 - P Q - 2 \alpha P S + \alpha S Q + (\alpha S)^2 \]  \hspace{1cm} (A4)

which is the same as

\[ (\alpha S)^2 + (\alpha Q - 2 \alpha P) S + (P^2 - P Q) = 0 \]  \hspace{1cm} (A5)

This can be written as the quadratic equation

\[ a S^2 + b S + c = 0 \]  \hspace{1cm} (A6)

where the coefficients, \( a \), \( b \), and \( c \) are known, and given by

\[ a = \alpha^2 \]  \hspace{1cm} (A7)
\[ b = \alpha Q - 2 \alpha P \]  \hspace{1cm} (A8)
\[ c = P^2 - P Q \]  \hspace{1cm} (A9)

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

\[ y = c + a S_t^2 = P(P - Q) + (\alpha S_t)^2 \]  \hspace{1cm} (A10)

and

\[ x = -b = 2 \alpha P + (1 - \alpha) Q \]  \hspace{1cm} (A11)

and where an initial value of the maximum storage, \( S_t \), is iterated until a stable estimate is achieved.

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