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Evaluating the Effects of Green Roofs as Tools for Stormwater Management in an Urban Metropolis

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EVALUATING THE EFFECTS OF VEGETATED ROOFS AS TOOLS FOR STORMWATER MANAGEMENT IN AN URBAN METROPOLIS

by

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Under the Direction of Dr. Jordan Clayton

ABSTRACT

Stormwater management is an essential aspect of urban hydrology. Urbanized areas have large amounts of impervious surface cover (ISC) and well developed sewer and drainage networks which rapidly channel water and pollutants off of streets and into local streams. This research evaluates the use of vegetated roofs as mechanisms to reduce ISC and stormwater runoff in downtown Atlanta. A 3-D model of the study site was created so that runoff rates could be measured for various rooftop scenarios under different size storm events. The results revealed a reduction in peak runoff and an increase in both the lag time and duration of response time. The results were most significant for the smallest storm event with 2/3 of the rooftops vegetated. As these experiments use a scale model for a section of downtown Atlanta, results are likely to be applicable to similar urban environments and may provide guidance for stormwater engineers.

INDEX WORDS: Urban hydrology, Impervious surface cover, Green roofs, Vegetated roofs, Low impact development

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For my family,

And the great city of Atlanta.

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CHAPTER 1

INTRODUCTION AND LITERARY REVIEW

Urban Hydrology

Storm water management is an essential aspect of urban hydrology as it relates to water quality and quantity. Urbanized areas are characterized as having large amounts of impervious surfaces and well developed sewer and drainage networks which rapidly channel water off of streets and into local streams (Sauer et al. 1983; Paul and Meyer, 2001; Nelson, et al. 2006). The combination of impervious surface cover and numerous storm drains cause urban streams to produce “flashy” hydrographs because they tend to have low base flow levels but experience large, rapid increases in discharge during storm events (Figure 1). Watersheds with as little as 10-20 percent impervious cover can result in substantial stream ecological degradation (Bledsoe and Watson, 2001; Booth, et al. 2004). Impervious surface cover effectively reduces groundwater infiltration rates and storage levels, which over time impairs useable water quantity and quality. As storm water is quickly carried from roads to streams in the form of runoff, a greater amount of surface pollutants are introduced into the stream because the water is unable to undergo the natural filtration process through the soil (Farahmand, et al. 2007). In addition, local groundwater supplies are reduced as the water is carried downstream and out of the basin instead of infiltrating and replenishing the local water table (Yin, 1993; Rose and Peters, 2000). Stream channels and the biotic life they support are highly sensitive to urbanization. Channels often undergo rapid erosion and incision which leads to a widening and deepening of the channel and

often times leads to a decline in biological health and variety (Bledsoe and Watson, 2001; Booth, et al. 2002; Watson, et al. 2002; Booth, et al. 2004).

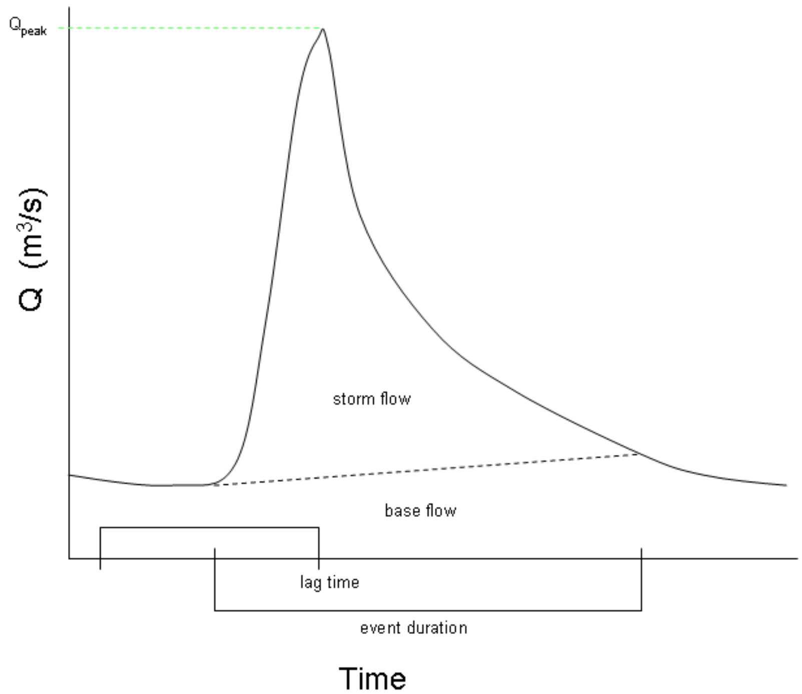

Figure 1: Sample “flashy” hydrograph showing the peak discharge, lag time, event duration, and base flow conditions (Figure by J. Clayton, used with permission)

As a way to promote the control of water loss due to runoff, low impact development (LID) methods are being considered and compared against traditional development techniques (Holman-Dodds, et al. 2003; Hood et al. 2007). Common LID storm water techniques include disconnected impervious surfaces, filter strips, porous pavement, bioretention, and cluster development. LID generally makes use of on-site detention and infiltration mechanisms to control rainfall-runoff, water quantity, and water quality to help reduce the negative impacts of urbanization (Hood, et al. 2007). Based on experiments from three basic scenarios of

development: an undeveloped landscape; a fully developed landscape using traditional, high impact storm water management; and a fully developed landscape using infiltration based, low impact design, results suggest that it is possible to reduce the negative impacts on hydrology due to urbanization by manipulating the landscape to include disconnected storm water systems (Holman-Dodds, et al. 2003). The degree of potential impact reduction is related to the size of the rainfall event as well as local soil texture, with the greatest reductions occurring during small, relatively frequent rainfall events in areas with more pervious soil textures (Holman-Dodds, et al. 2003). Low impact techniques appear to provide the most benefits for reducing runoff for the events that see the greatest relative increases from urbanization: those generated by the small, frequent rainfall events that are small enough to produce little or no runoff from pervious surfaces, but do produce runoff for impervious areas (Holman-Dodds, et al. 2003). The greatest benefits of infiltration based storm water management are the potential to reduce frequent flooding of urban streams which helps to reduce channel erosion as well as increase base flows which helps to restore and improve stream water quality (Ferguson and Suckling, 1990). Therefore, the goal of LID is to reduce urban storm water pollution and channel degradation by mimicking predevelopment site hydrology. However, there is currently a shortage of research pertaining to LID compared to traditional development, creating a need to link specific development types with hydrologic impacts (Hood, et al. 2007), particularly as related to the use of vegetated rooftops.

Vegetated Roofs

Controlling storm water runoff from impervious surfaces is an important goal because of the disruptions high intensity runoff flows have on downstream ecosystems, water quality and

quantity, and property owners in floodplain areas (Carter and Rasmussen, 2006). A variety of policy tools have been implemented to alleviate the impact impervious surfaces have on urban watersheds. One strategy has been to place a limit on the total amount of impervious area in a given watershed. For example, the Georgia Planning Act of 1989 limited impervious area in small watersheds to 25%, or existing use, whichever is greater (Carter and Jackson, 2006). Limiting impervious surfaces, however, can be highly problematic and politically unfeasible due to conflicting economic interests because land is extremely valuable from a developer's standpoint (Carter and Jackson, 2006). In addition, existing land use in urban centers often exceeds the 25% threshold. An alternative approach to limiting impervious areas is to encourage storm water managers to alleviate the environmental impact of storm water from impervious surfaces through the use of storm water best management practices (BMPs) (Carter and Jackson, 2006). BMPs use low impact development techniques to reduce storm water impacts on receiving streams by increasing storm water storage areas across a watershed, slowing the flow of water into the receiving water body, and/or replacing impervious surfaces with pervious areas that allow for infiltration (Carter and Jackson, 2006).

Because land availability is limited in highly urbanized areas, there is an increasing need for land uses that serve multiple purposes. One feasible method for reducing storm water runoff is through the use of vegetated (green) roofs, which efficiently detain and retain storm water when compared to conventional (black or concrete) roofs (Carter and Rasmussen, 2006). Roofs, however, have traditionally been overlooked in the United States as tools for storm water management and urban environmental problems even though roof tops constitute a substantial proportion of the total impervious surface cover (ISC) in highly developed watersheds where the ISC exceeds 50% (Van Woert, et al. 2005; Carter and Rasmussen, 2006). Recent studies have

documented how the use of thin-layered vegetated roof systems allows rooftops to serve both as a structural component of the building, and also as a storm water management tool (Carter and Jackson, 2006). “Green roofs use engineered growing media, drought tolerant plants, and specialized roofing materials installed on existing structures, creating a rooftop that can absorb and retain water rather than quickly shedding it into storm water conveyance systems” (Carter and Rasmussen, 2006, p.1262). Studies have shown that retrofitting existing buildings with a green roof can significantly reduce and in some cases eliminate the storm water contribution from the existing structure (Carter and Rasmussen, 2006).

Carter and Jackson (2006) conducted green roof studies on four spatial scales to account for land use diversity within a watershed. They also modeled the discharge of the receiving water body under hypothetical roof greening scenarios to determine the effect that green roofs have on the flow regime of an urban stream system (Carter and Jackson, 2006). Finally, they examined how widespread green roof implementation may be used to accomplish statewide storm water management goals.

Van Woert and colleagues (2005) tested the effects of roof slope and media depth to determine the best possible combination for the maximum retention of storm water. They tested the influence of two roof slopes (2 and 6.5%) and green roof media depths (2.5, 4.0, and 6.0cm). The 2% slope was tested using media depths of 2.5 and 4.0cm and the 6.5% slope was tested using media depths of 4.0 and 6.0cm. Their results indicated that a vegetated roof with a 2% slope and a 4cm media depth had the greatest retention at 87%. They concluded that a combination of a reduced slope and deeper growing media significantly reduces the total quantity of storm water runoff.

Flat top roofs are the best candidates for implementing the use of vegetation, and are most often found in commercial, industrial, and institutional (university) areas, as opposed to residential areas where rooftops are often sloped (Van Woert, et al. 2005; Carter and Jackson, 2006). Green roofs appear to provide the greatest benefit during small rainfall events, which tend to be more frequent than large rainfall events in most regions. Small events exhibit the greatest retention rates because as soils become saturated (in larger events) they generate overland runoff much the same as impervious surfaces. Essentially, vegetated roofs function similarly to the interception process found in forested sites, because their purpose is to retain water and release it slowly back into the atmosphere through evapotranspiration (Carter and Jackson, 2006). Thus, green roofs are best suited for places that receive relatively small amounts of precipitation throughout the year, and not places that receive relatively large but infrequent events. In addition, places that receive a large portion of precipitation from snow are also less likely to experience significant hydrological benefits from green roofs.

Carter and Jackson's (2006) results suggest that although green roofs have proven to be an effective means of storm water management, they should not be exclusively relied upon to provide complete storm water management at the watershed scale. However, for the most highly urbanized areas, green roofs do appear to effectively reduce peak discharges and increase the lag time between peak rainfall and peak discharge (Carter and Jackson, 2006). Green roofs may also extend the duration of response in a receiving stream or water body. All of these benefits help to reduce stream power and erosion as well as help to reduce flood frequencies and magnitudes.

In addition to reducing storm water runoff, which reduces water pollution and channel erosion, vegetated roofs have other benefits as well. Saiz et al. (2006) investigated the comparative life span of standard versus green roofs as an evaluation of the benefits to installing

green roof systems. They found the key property of a green roof to be its lower solar absorption, which causes lower surface temperatures, which then reduces the heat flux through the roof as compared to traditional, black roof surfaces. Their results indicated a great reduction in energy costs of a building, particularly in regards to energy savings for space cooling. Additionally, the reduction in solar absorption of the green roof extends the life span of the roof because the fibers do not get over stressed from extreme temperature fluctuations.

Furthermore, the addition of vegetation on rooftops has the ability to reduce the urban heat island effect, clean the air, and provide micro-habitats for insects and birds in densely developed metropolitan areas. The plants and soil absorb heat rather than reflecting it back into the immediate atmosphere, and the process of evapotranspiration provides local cooling as water vapor is slowly released into the air. The plants help clean the air by absorbing carbon dioxide via photosynthesis while at the same time native plant species provide food and shelter to small animals who may be struggling to survive in the urban environment.

Chicago is currently leading the nation in green roofs, with more than two million square feet covered with low-growing sedums, native grasses, herbs, and shrubs (Berkooz, 2007). Local planners, developers, citizens, and designers in Ann Arbor, Michigan are encouraging the construction of green rooftops for a variety of reasons, including storm water management and energy saving costs. The energy efficiency of green roofs appears to be their biggest selling point, with the potential to cut energy costs by 30%. Government buildings tend to be the first buildings to convert to green roofs, and in Ann Arbor, the money that government buildings save in energy costs will be directed towards climate study programs, so that the benefits can be multiplied even further (Berkooz, 2007).

Atlanta Area

The Middle-Upper Chattahoochee basin has experienced rapid increases in development and as a result, urban streams now have higher flood frequencies and magnitudes than rural streams under the same precipitation regimes (Yin, 1993). The land use change in this area has gone from mostly wooded to highly developed, with large amounts of impervious surfaces. Ferguson and Suckling (1990) reported that the Atlanta area population more than doubled from 1960 to 1985 and impervious surface cover experienced a similar rate of increase during this time period. Lo and Yang (2002) noted that the Atlanta area's population increased by another 40 percent from 1990 to 2000. As Atlanta's population has grown, impervious surfaces from urban development and sprawl have replaced croplands, grasslands, and forested areas with high-density and low-density urban centers. High-density urban use is defined as having approximately 80-100% construction materials including large buildings, roads, and parking lots with relatively low residential development. Low-density urban use is defined as having approximately 50-80% construction materials comprised mostly of residential development with up to 20% vegetation cover. In 1973, the metro Atlanta area was comprised of 29,722 ha (2.85%) of high-density urban cover and 76,910 ha (7.36%) of low-density urban cover, and by 1999, high-density urban cover increased to 87,477 ha (8.3%) and low-density urban cover increased to 282,959 ha (27.1%), with these numbers expected to rise in the future (Lo and Yang, 2002). These increases in high-density and low-density urban land cover equate to a 34% and 27% increase, respectively, over a 26 year period. The transition towards a more high-density urbanized landscape has hydrologic significance because it greatly reduces the opportunity for rainfall infiltration and thus leads to an increase in overland flow and localized flooding and erosion.

Yin (1993) conducted a study focused on high frequency but low magnitude storms (an often neglected realm of study) because of their importance to the overall water supply and effects on local water quality. The study focused on the fully developed Peachtree Creek urban basin, the partially developed Big Creek basin, and the rural Snake Creek basin. Yin's 1993 results show that the urban stream has more frequent high and very low magnitude flows than the rural stream; similar trends have been observed for the 1990's and 2000's (B. Smucygz et al., submitted manuscript). These results further reinforce the idea that under similar precipitation conditions, urban basins flood more frequently than rural basins (Yin, 1993). However, as storm magnitude increases, the difference between the urban and rural basins is reduced because a natural surface may behave similarly to an impermeable surface when the soil is completely saturated, therefore, the extreme flood events in both urban and rural environments may have similar regimes (Yin, 1993). The installation of green roofs may help to reduce flooding and channel erosion along Peachtree Creek by reducing the amount of storm water that rapidly enters the stream during frequent but fairly small storm events.

Purpose of the Study

This study sought to explore and evaluate the urban hydrological benefits of vegetated roofs as they relate to storm water management in downtown Atlanta, Georgia. Specifically, this study evaluated the ability of green roofs to retain storm water and (1) reduce the peak discharge volume entering near by streams, (2) increase the lag time between peak rainfall and peak stream discharge, and (3) increase the duration of response by receiving water bodies. A 3-D, "scale" table-top model of the study area was constructed and tested with hypothetical rainfall events under various green rooftop percentage cover scenarios. Runoff was collected at the outlet of the

table-top model and measured for volume, lag time, and duration. This study provides a unique contribution to our understanding of the hydrological benefits of green roofs through the empirical testing of different size storm events for different rooftop cover conditions at the (3-D modeled) sub-watershed level. A spatial analysis was conducted in order to determine the percentage of green roofs needed to have the most effective impact with regards to storm water management in the study domain. Because the model is a scaled-down section of downtown Atlanta, results should be widely applicable to other similar urban environments.

The downtown Atlanta area, and particularly the Georgia State University campus, was chosen as the study site for this research because it has a large amount of impervious surface cover as well as a large collection of flat roof buildings which are ideal for retrofitting with a vegetated roof. The Atlanta area also has an average rainfall of 48 inches per year, most of which falls during small rainstorm events, which is also ideal for green roofs to be most effective. Currently, there is a shortage of green roof studies in the United States, and there have not been any green roof studies conducted for the Atlanta area, nor have there been any tabletop experimental studies of green roofs, so far as we know. This research hopes to add to the small collection of American green roof studies as well as promote their use in downtown Atlanta for the purpose of stormwater management.

Anticipated Outcomes

Based on previous work and hydrologic reasoning, it was expected that a certain percentage of green roof cover would result in a corresponding percentage of reduction in storm water runoff. Green roof cover should reduce the flashiness of urban hydrographs by increasing the lag time between the onset of the storm and the peak discharge in a receiving stream. Green

roofs should also reduce the total peak discharge because they will reduce the total volume of runoff by detaining rain water and releasing it gradually back to the atmosphere through the process of evapotranspiration. An increased lag time, reduction in peak discharge, and extension of stream response time should all contribute to alleviating localized urban flooding and stream bank erosion. However, the strongest effects of green roofs were expected to be found in changes in lag times and peak discharges because of the likely reduction in overall runoff volume and velocity.

CHAPTER 2

METHODOLOGY

Model Construction

In order to identify potential rooftops that can act as effective storm water management features, Google Earth was used to view roofs in the study domain to evaluate their potential to become successful water detention sites (Figure 2). Google Earth provides a vertical birds-eye view of the buildings as well as a 3-D view, and also allows one to tilt the perspective to observe a horizontal angle that allows for the calculation of slope in the roofs. Flat roofs are the best candidates but gently sloped (2-6.5%) roofs can also be used (VanWoert, et al. 2005). Buildings were selected based on roof slope, roof size, and location within the basin. Buildings located closer to streams are ideal because they would effectively slow the initial flow of runoff into a stream; however all buildings within a basin can be helpful in contributing to runoff reduction.

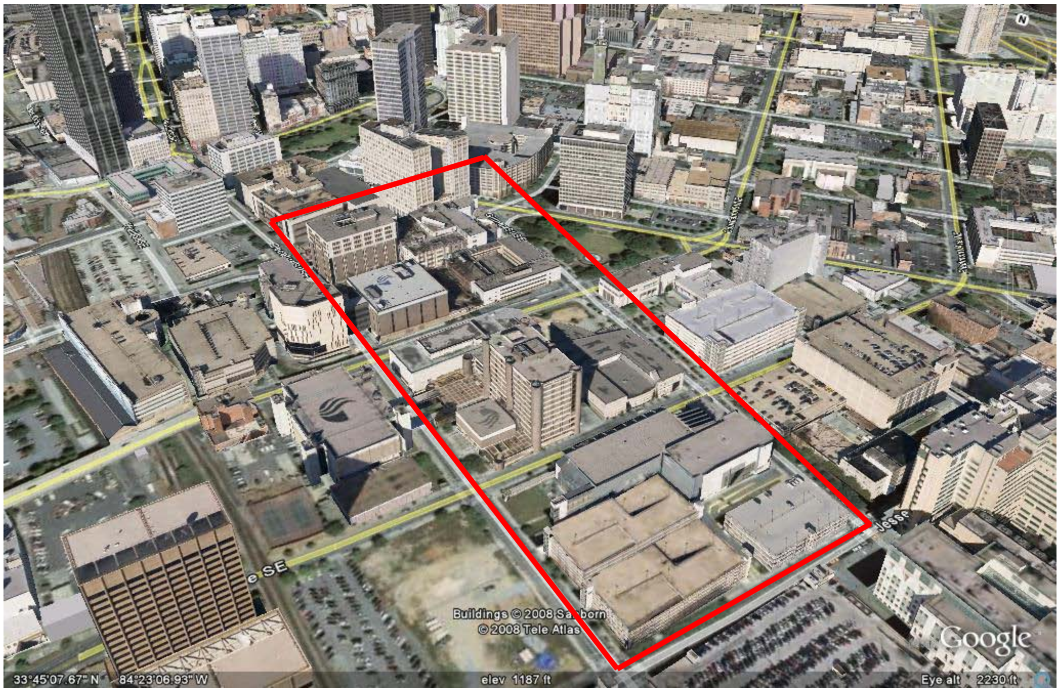

Figure 2: Google Earth Image of downtown Atlanta and Georgia State University main campus, the study area is outlined in red

A GIS generated map of the study area was created to show which buildings are most suited to hold a green roof (Figures 3 and 4). Buildings were selected based on size, roof slope, and function (building versus parking deck). In order to model the effect of increasing vegetated roof density on hydrologic response for a range of precipitation magnitudes, the selected area was constructed on a 1 m x 3 m board at a scale of 1:160. The study area was chosen because of the buildings' large size, flat roofs, and high density. I also wanted the study site to be entirely on Georgia State University's campus, thus these three city blocks were ideal. I built the model on an oriented strand board, which is an engineered wood panel made from compressed wood strands arranged in three perpendicular layers and bonded with an adhesive resin. This gave the board some texture which helped to mimic real world impervious surface cover. A 'curb-like' barrier was placed around the edge of the model in order to direct the runoff to a single outlet so that it could easily be captured and measured. The board was painted with a high-gloss water-

proof lacquer to prevent water loss due to seepage, and then spray painted with a glossy black paint to further protect it from water damage (Figure 5). Posts were attached to the underside of one end of the board to create the 0.025 slope, which is the approximate slope of the land surface in this portion of the modeled landscape, as calculated using Google Earth.

Three city blocks were constructed, each scaled down to one square meter in size. The building footprints were drawn onto the board at a 1:160 scale, and then built up using one inch thick foam board to uniform vertical heights. It was not necessary to reproduce each building's vertical scale because differences in the downward travel time of water draining the rooftops are at least an order of magnitude smaller than observed differences in runoff production. Each footprint was given a rim around the top so that they could later retain soil and vegetation. The rims, also made of foam board, were attached using foam glue and then reinforced with caulk (Figures 6-9). Drain holes were drilled into the tops so that the water could mimic rooftop runoff found in the real world. The board was then placed on a hand-made table built with four corner posts with a screen stretched across the top (Figure 10). The screen was included to help disperse the "rain" more evenly.

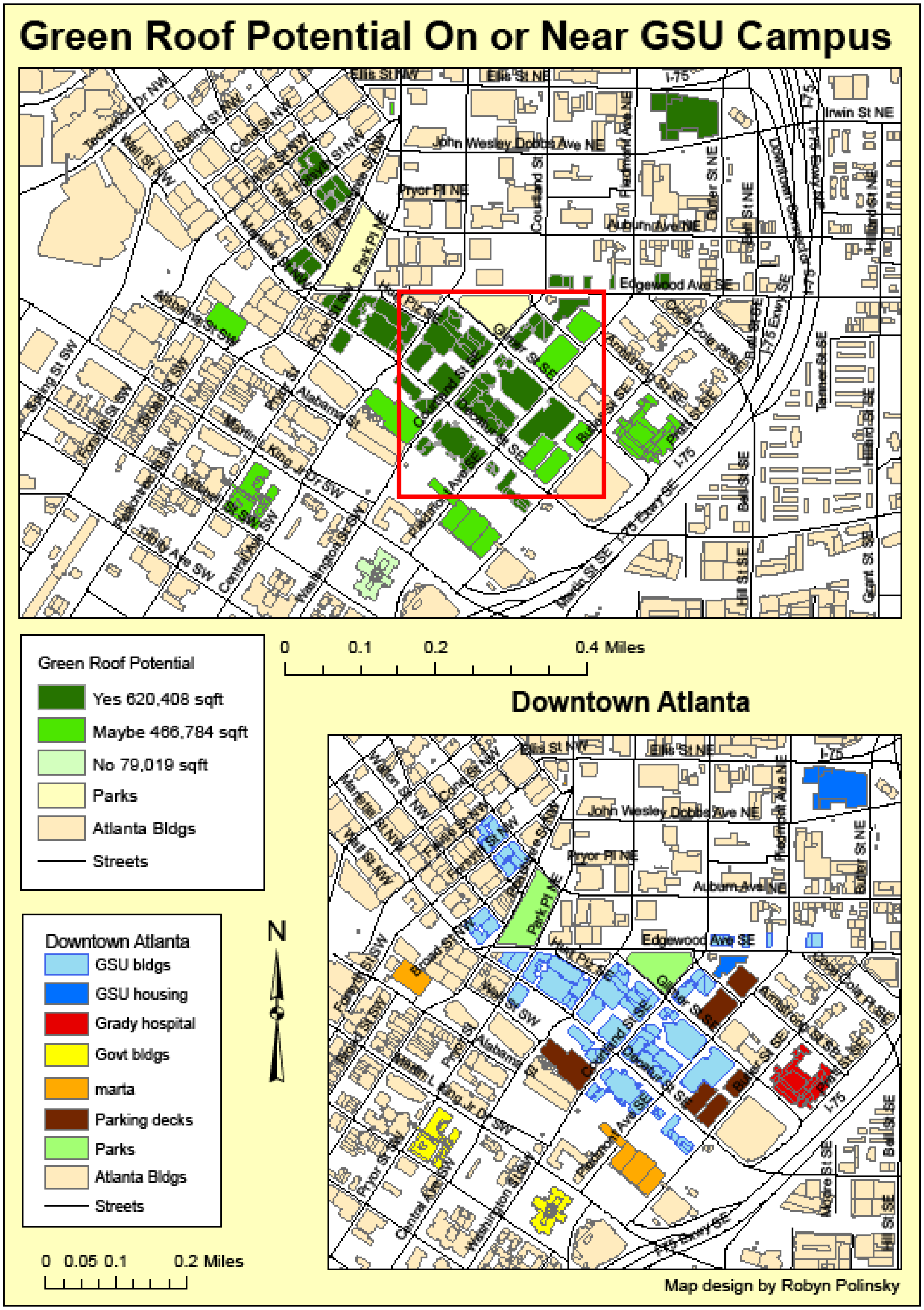

Figure 3: Map of study area showing GSU green roof potential

Figure 4: Detail of the three city blocks chosen for this study

Figure 5: The 1 m x 3 m board with a ‘curb-like’ barrier around the edge and one outlet

Figure 6: Model construction of GSU main quad, this block is farthest from the outlet

Figure 7: Model construction of the Student Center, University Center, and Recreation Center

Figure 8: Model construction of the Recreation Center and Parking decks S, N, and K; this block is closest to the outlet

Figure 9: Buildings in place on the board before being lifted onto the table, the board slopes down towards the right

Figure 10: Handmade table with a screen stretched across the top, the model will be placed on the board below the screen

Experiment Design

The 3-D table-top model was used to measure runoff rates for different size storm events under different rooftop cover scenarios in the study site. A hose with a spray nozzle of known discharge was used to simulate various intensities of a 5 minute rainstorm event (approximately 0.25 in, 0.5 in, and 0.75 in depth). All runoff flowed out of a single outlet and was collected by a bucket marked with one quart increments; the depth was estimated each minute to 0.1 quart. Three rain gauges were placed inside the model so that precipitation intensities could be measured accurately. Each rain gauge and the runoff receptacle were measured and recorded at one minute intervals, (which was the smallest manageable temporal resolution for a 4-person team). Because all of the water was captured and measured, the model represented a closed system.

First, three tests were conducted for the impermeable roofs (no vegetation) under the three different rainfall intensities, each of which was run three times for quality assurance. Discharge volume, lag time, and duration measurements were recorded and averaged for each event to establish the control. Next, roofs deemed as excellent (model) candidates (due to their smaller sizes and more simplistic shapes which made them easier to work with, and corresponded to roughly one-third of the horizontal extent of the combined rooftops) were vegetated with a thin layer (about 1/2 inch) of soil and alfalfa sprouts. The soil used in the model has a course, sandy texture and is the same as that used on actual vegetated rooftops. It is a special blend designed for extensive green roofs and is composed of 80% stalite expanded slate (coarse) and 20% compost (worm castings). The sandy texture allows for high permeability but does not retain moisture very long due to its low suction capacity, and thus is ideal for rooftop vegetation. The alfalfa seeds were evenly dispersed across the top of the soil and given a small

amount of water. The sprouts reached maturity in 5-6 days and were then ready to be used in the model (Figures 11-16). Runoff rates were measured again for the same three precipitation intensities. Finally, roofs deemed as good or possible (model) candidates, (due to their larger sizes and more complex shapes which made them harder to move and thus work with) were also vegetated and runoff measurements were again recorded for all storm sizes. About 2/3 of the roofs were vegetated for this last round of testing (Figure 17). Therefore, a total of fifteen tests were conducted.

Figure 11: Model being tested with 1/3 of the rooftops vegetated

Figure 12: Detail image of alfalfa sprout growth

Figure 13: Testing the small rain event with 1/3 of the rooftops vegetated

Figure 14: Runoff flowing into the bucket marked in one quart increments

Figure 15: This image was taken during the last minute of testing the small rain event with 1/3 of the rooftops vegetated

Figure 16: Detail image of runoff flowing into the bucket marked in one quart increments

Figure 17: Image showing 2/3 of the rooftops vegetated

Model hydrographs were created from the discharge data for each model run, focusing, in particular, on the peak discharge, lag time, and runoff duration. Using these data, estimates can be made as to how much storm water runoff may be reduced by green roofs in the study domain, as well as what percentage of the total rooftops need to be vegetated in order to have a significant impact on urban stream hydrology.

CHAPTER 3

RESULTS

Control

In order to establish baseline conditions, the control tests (those without vegetation) were run three times for each storm event. The results of each were averaged and are presented in Tables 1-6 and Figures 18-23. The tables provide the exact rainfall and runoff depths as well as their rate per minute. The hydrographs show graphic trends of the three variables of interest.

Table 1: Small rainfall event for the control conditions (averaged from three gauges)

Time (Min.)	**Depth (Inches)**	**Rate/Min**
0	0	0
1	0.01	0.01
2	0.05	0.04
3	0.11	0.06
4	0.16	0.05
5	0.19	0.03
6	0.19	0

Table 2: Small rainfall event runoff for the control conditions, no vegetation (averaged from three tests)

Time (Min.)	**Depth (Quarts)**	**Rate/Min**
0	0	0
1	0	0
2	0.25	0.25
3	0.75	0.5
4	1.5	0.75
5	2.75	1.25
6	3.95	1.2
7	4.4	0.45
8	4.75	0.35
9	4.9	0.15
10	5	0.1
11	5	0

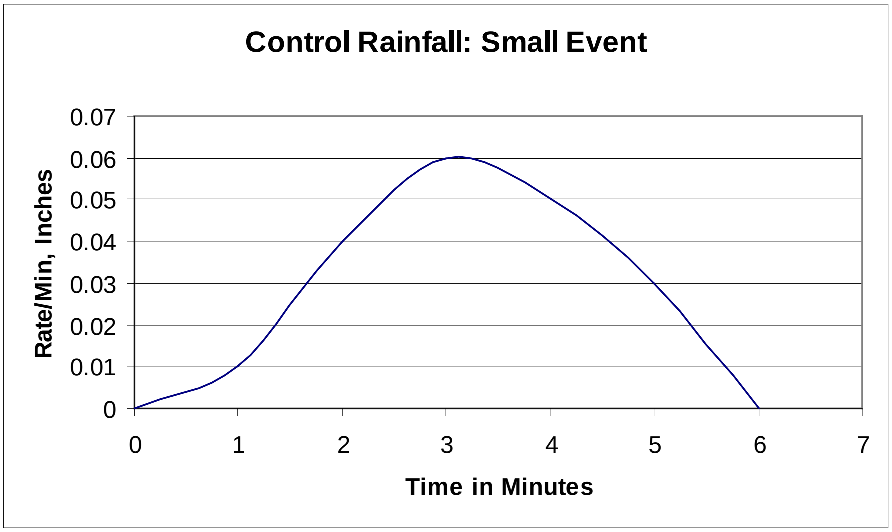

Figure 18: Control rainfall, small event average rate/minute in inches

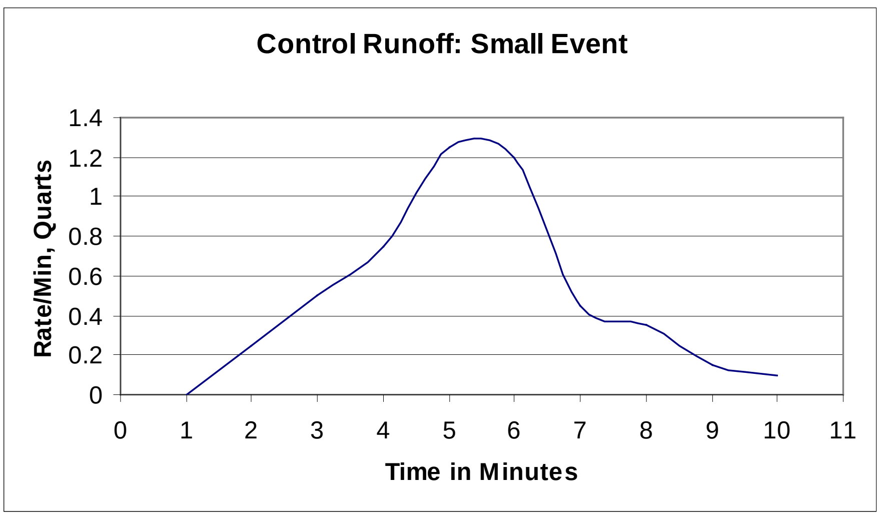

Figure 19: Control runoff, no vegetation, small event average rate/minute in quarts

Table 3: Medium rainfall event for the control conditions (averaged from three gauges)

Time (Min.)	Depth (Inches)	Rate/Min
0	0	0
1	0.1	0.1
2	0.22	0.12
3	0.37	0.15
4	0.5	0.13
5	0.63	0.13
6	0.63	0

Table 4: Medium rainfall event runoff for the control conditions, no vegetation (averaged from three tests)

Time (Min)	Depth (Quarts)	Rate/Min
0	0	0
1	0	0
2	0.6	0.6
3	2.1	1.5
4	3.8	1.7
5	5.5	1.7
6	7	1.5
7	7.5	0.5
8	7.8	0.3
9	7.9	0.1
10	8	0.1
11	8	0

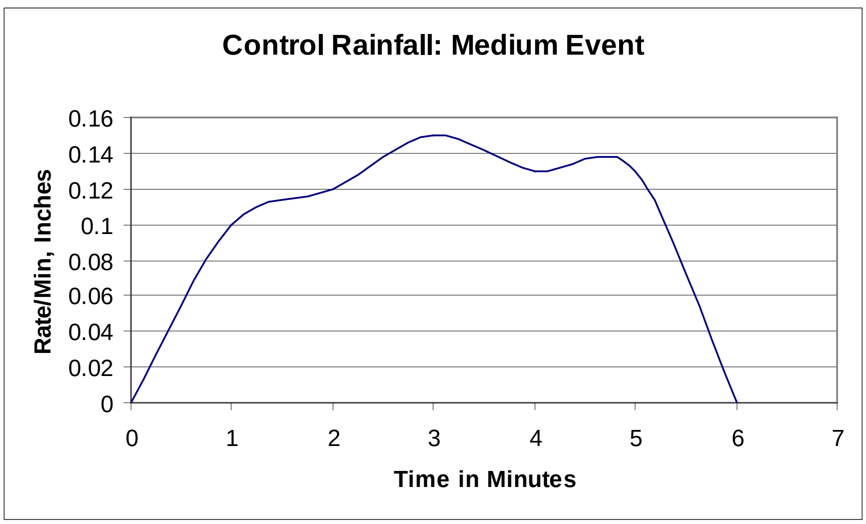

Figure 20: Control rainfall, medium event average rate/minute in inches

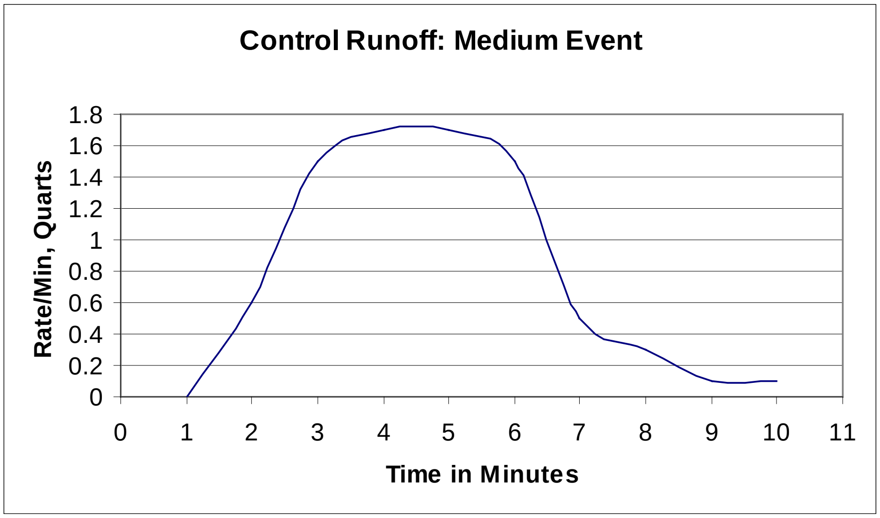

Figure 21: Control runoff, no vegetation, medium event average rate/minute in quarts

Table 5: Large rainfall event for the control conditions (averaged from three gauges)

Time (Min)	Depth (Inches)	Rate/Min
0	0	0
1	0.16	0.16
2	0.35	0.19
3	0.54	0.19
4	0.67	0.16
5	0.82	0.15
6	0.82	0

Table 6: Large rainfall event runoff for the control conditions, no vegetation (averaged from three tests)

Time (Min)	Depth (Quarts)	Rate/Min
0	0	0
1	0.9	0.9
2	3.9	3
3	8	4.1
4	13	5
5	17	4
6	19.8	2.8
7	20.5	0.7
8	20.8	0.3
9	20.9	0.1
10	20.9	0

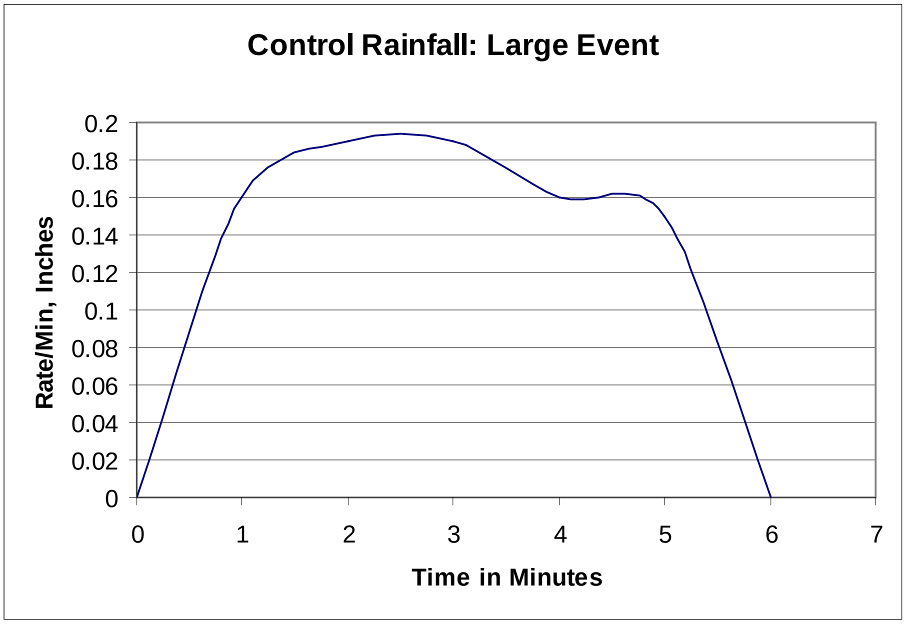

Figure 22: Control rainfall, large event average rate/minute in inches

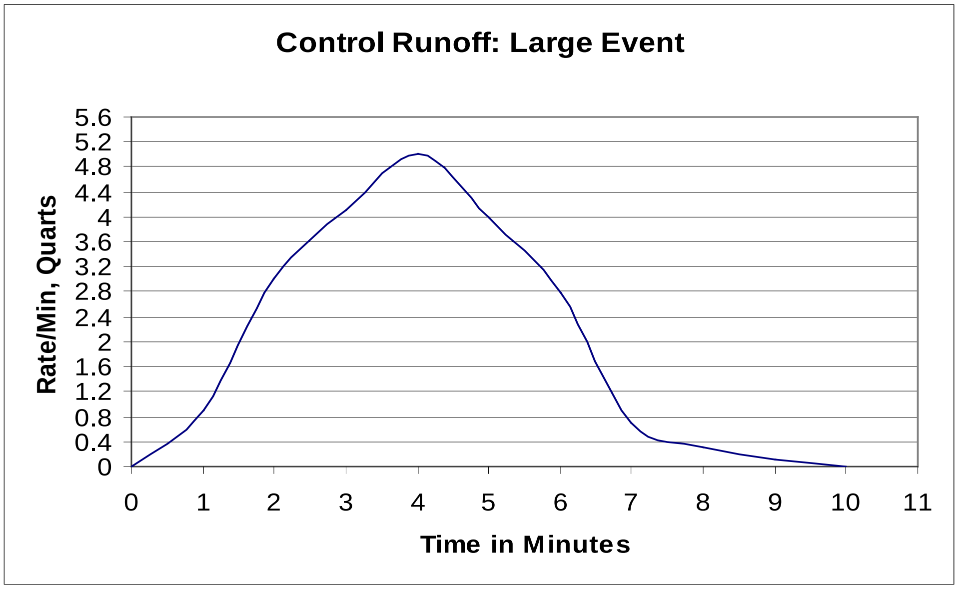

Figure 23: Control runoff, no vegetation, large event average rate/minute in quarts

One-third Vegetation

After completing the control tests, approximately one-third of the roof tops were covered with soil and alfalfa seeds. The seeds fully germinated within 5-6 days and the tests were run again. Each storm event was tested only once due to the time it takes for the antecedent moisture to dry (at least one full day was allowed in between tests). The results of these tests are displayed in Tables 7-12 and Figures 24-29.

Table 7: Small rainfall event with 1/3 of the rooftops vegetated (averaged from three gauges)

Time (Min)	**Depth (Inches)**	**Rate/Min**
0	0	0
1	0.01	0.01
2	0.04	0.03
3	0.09	0.05
4	0.16	0.07
5	0.19	0.03
6	0.19	0

Table 8: Small rainfall event runoff with 1/3 of the rooftops vegetated

Time (Min)	**Depth (Quarts)**	**Rate/Min**
0	0	0
1	0	0
2	0.25	0.25
3	0.5	0.25
4	0.8	0.3
5	1.4	0.6
6	2.1	0.7
7	2.9	0.8
8	3.2	0.3
9	3.3	0.1
10	3.3	0

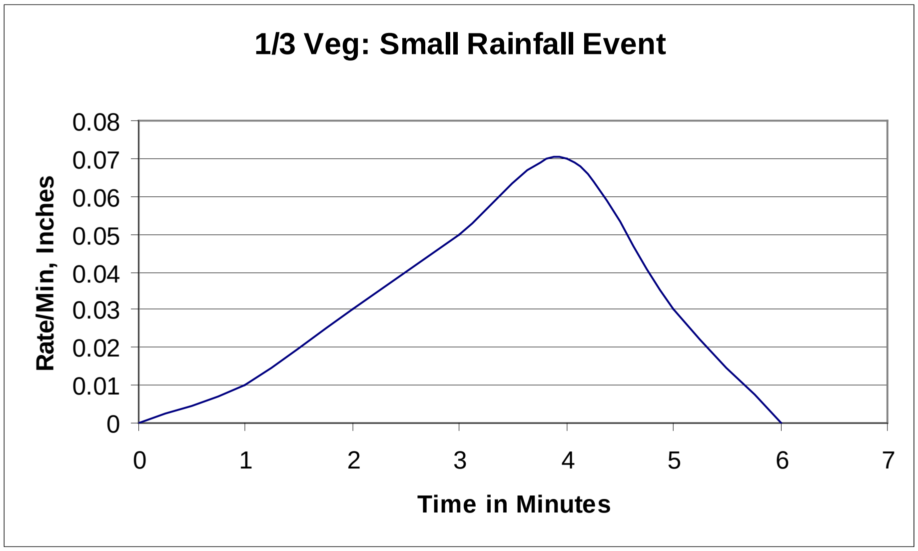

Figure 24: Small rainfall event rate/minute in inches with 1/3 of rooftops vegetated

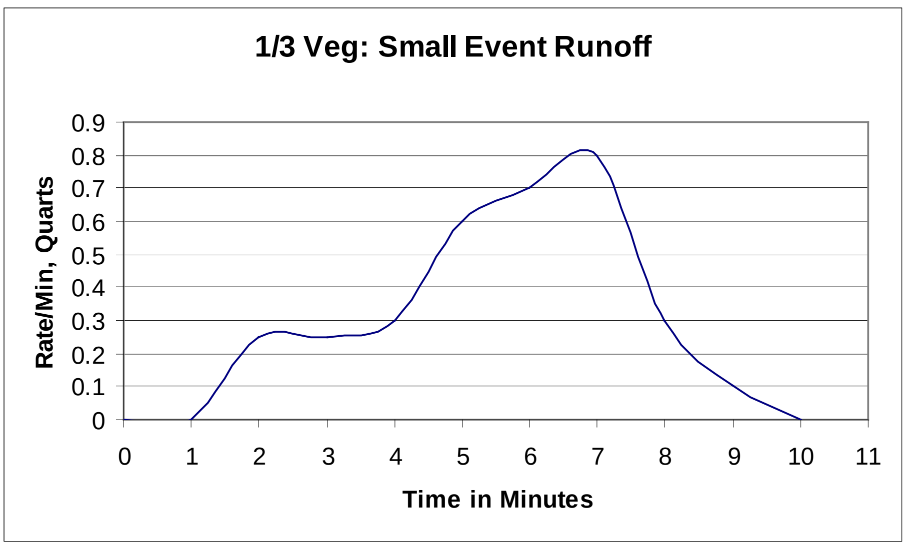

Figure 25: Small event runoff rate/minute in quarts with 1/3 of the rooftops vegetated

Table 9: Medium rainfall event with 1/3 of the rooftops vegetated (averaged from three gauges)

Time (Min)	**Depth (Inches)**	**Rate/Min**
0	0	0
1	0.11	0.11
2	0.25	0.14
3	0.4	0.15
4	0.55	0.15
5	0.65	0.1
6	0.65	0

Table 10: Medium event runoff with 1/3 of the rooftops vegetated

Time (Min)	Depth (Quarts)	Rate/Min
0	0	0
1	0	0
2	0.3	0.3
3	1.1	0.8
4	2	0.9
5	3.2	1.2
6	4.8	1.4
7	5.5	0.7
8	6	0.5
9	6.4	0.4
10	6.8	0.4
11	6.85	0.05
12	6.85	0

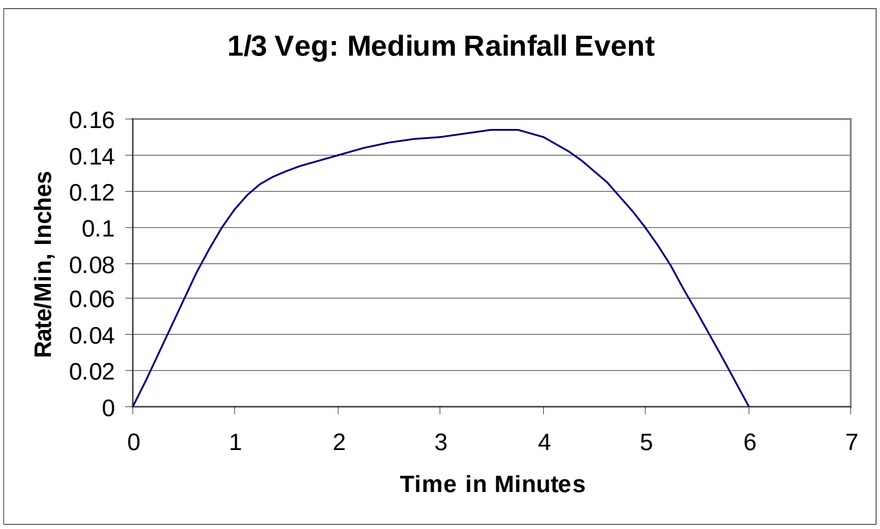

Figure 26: Medium rainfall event rate/minute in inches with 1/3 of the rooftops vegetated

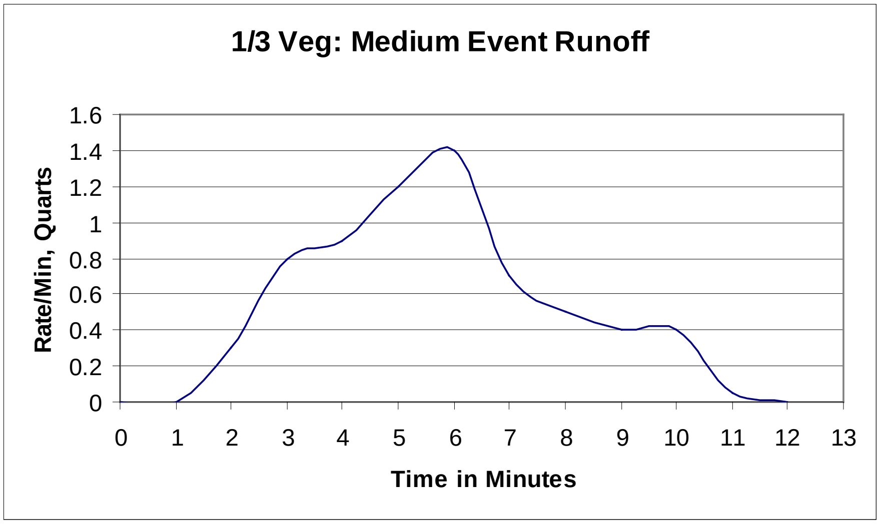

Figure 27: Medium event runoff rate/minute in quarts with 1/3 of the rooftops vegetated

Table 11: Large rainfall event with 1/3 of the rooftops vegetated (average from three gauges)

Time (Min)	Depth (Inches)	Rate/Min
0	0	0
1	0.15	0.15
2	0.35	0.2
3	0.55	0.2
4	0.72	0.17
5	0.85	0.13
6	0.85	0

Table 12: Large rainfall event runoff with 1/3 of the rooftops vegetated

Time (Min)	Depth (Quarts)	Rate/Min
0	0	0
1	0.8	0.8
2	4	3.2
3	7.5	3.5
4	11.3	3.8
5	16.5	5.2
6	19.1	3.1
7	19.5	0.4
8	19.6	0.1
9	19.7	0.1
10	19.8	0.1
11	19.9	0.1
12	19.95	0.05
13	20	0.05
14	20	0

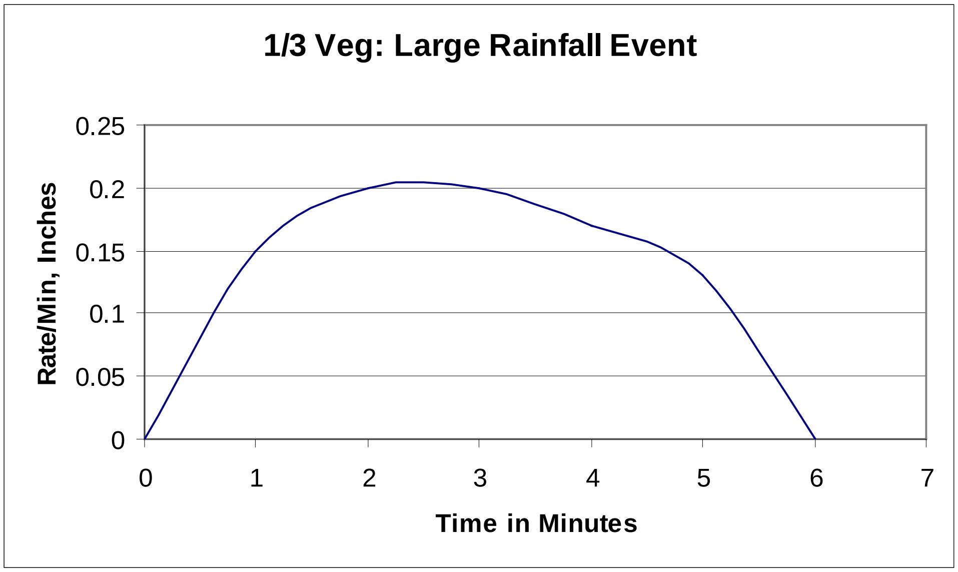

Figure 28: Large rainfall event rate/minute in inches with 1/3 of the rooftops vegetated

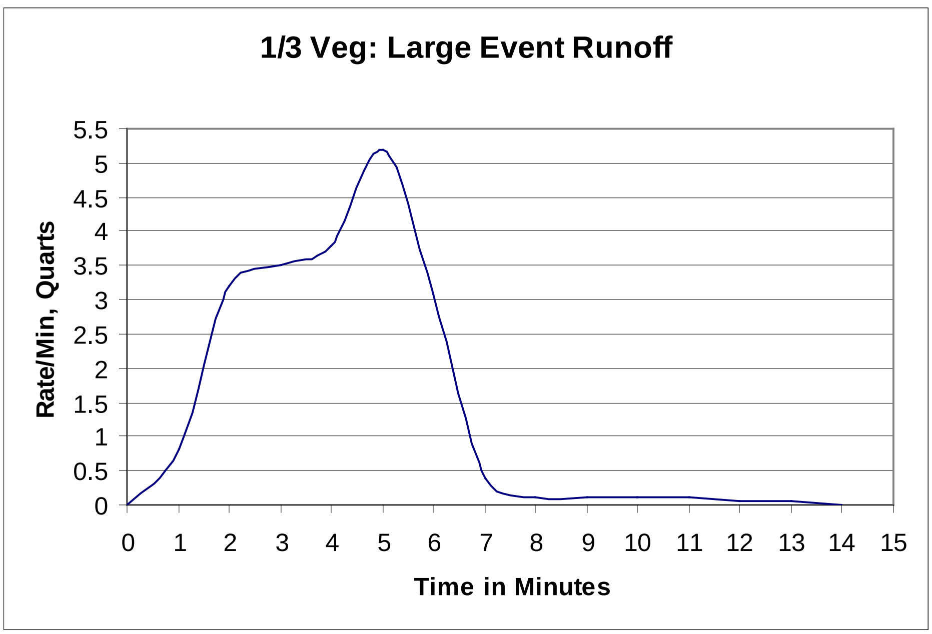

Figure 29: Large event runoff rate/minute in quarts with 1/3 of the rooftops vegetated

Two-thirds Vegetation

The final round of testing was done with approximately two-thirds of the rooftops vegetated. The results from these tests are displayed in Tables 13-18 and Figures 30-35. Synthesis of these results and details regarding differences in experimental runoff response are given in the following section.

Table 13: Small rainfall event with 2/3 of the rooftops vegetated (averaged from three gauges)

Time (Min)	**Depth (Inches)**	**Rate/Min**
0	0	0
1	0.04	0.04
2	0.08	0.04
3	0.13	0.05
4	0.17	0.04
5	0.2	0.03
6	0.2	0

Table 14: Small event runoff with 2/3 of the rooftops vegetated

Time (Min)	**Depth (Quarts)**	**Rate/Min**
0	0	0
1	0	0
2	0	0
3	0.25	0.25
4	0.6	0.35
5	1	0.4
6	1.5	0.5
7	2.2	0.7
8	2.35	0.15
9	2.4	0.05
10	2.45	0.05
11	2.5	0.05
12	2.5	0

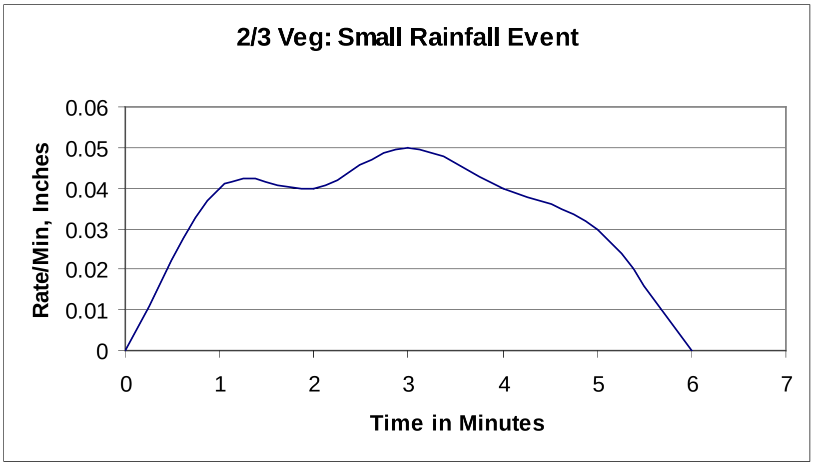

Figure 30: Small rainfall event rate/minute in inches with 2/3 of the rooftops vegetated

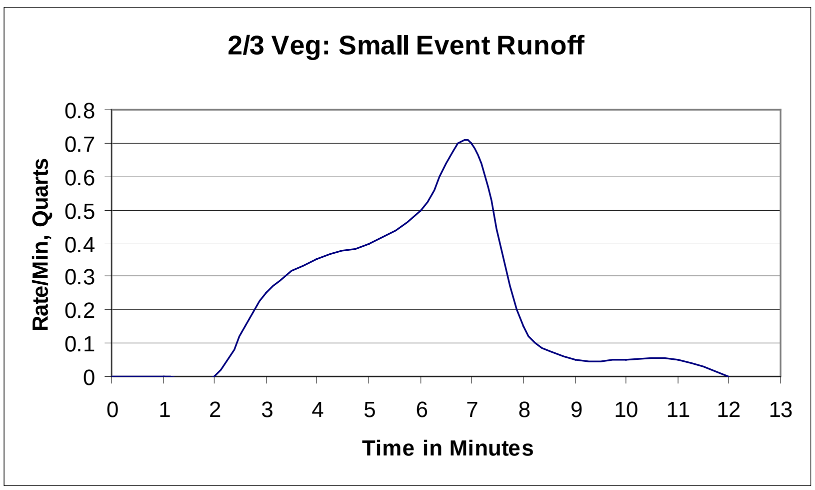

Figure 31: Small event runoff rate/minute in quarts with 2/3 of the rooftops vegetated

Table 15: Medium rainfall event with 2/3 of the rooftops vegetated (average from three gauges)

Time (Min)	Depth (Inches)	Rate/Min
0	0	0
1	0.09	0.09
2	0.21	0.12
3	0.35	0.14
4	0.5	0.15
5	0.62	0.12
6	0.62	0

Table 16: Medium event runoff with 2/3 of the rooftops vegetated

Time (Min)	Depth (Quarts)	Rate/Min
0	0	0
1	0	0
2	0.1	0.1
3	0.8	0.7
4	1.7	0.9
5	2.7	1
6	3.8	1.1
7	5.0	1.2
8	5.25	0.25
9	5.3	0.05
10	5.34	0.04
11	5.37	0.03
12	5.4	0.03
13	5.4	0

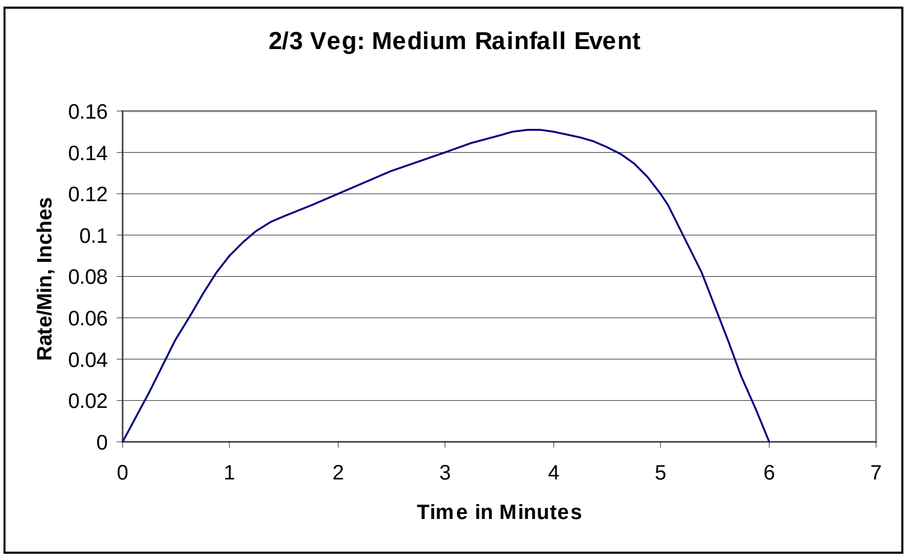

Figure 32: Medium rainfall event rate/minute in inches with 2/3 of the rooftops vegetated

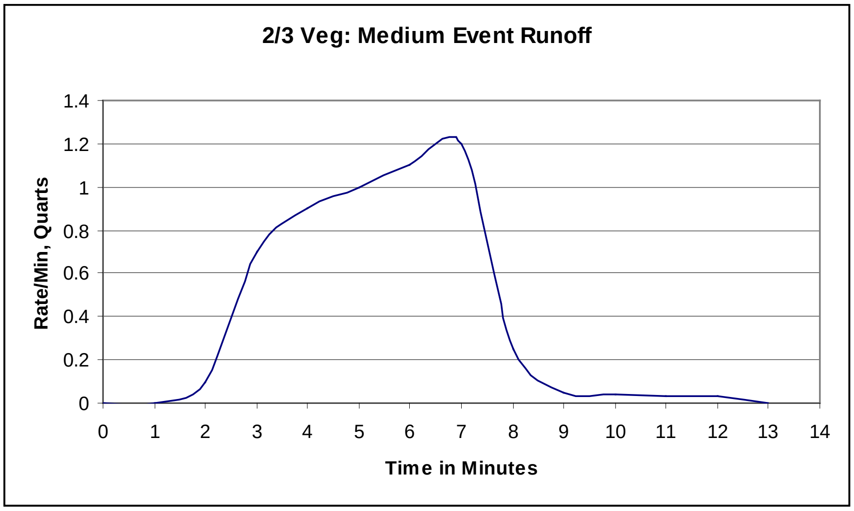

Figure 33: Medium event runoff rate/minute in quarts with 2/3 of the rooftops vegetated

Table 17: Large rainfall event with 2/3 of the rooftops vegetated (average from three gauges)

Time (Min)	Depth (Inches)	Rate/Min
0	0	0
1	0.16	0.16
2	0.35	0.19
3	0.54	0.19
4	0.7	0.16
5	0.84	0.14
6	0.84	0

Table 18: Large event runoff with 2/3 of the rooftops vegetated

Time (Min)	Depth (Quarts)	Rate/Min
0	0	0
1	0.3	0.3
2	0.8	0.5
3	1.7	0.9
4	3.8	2.1
5	7.0	3.2
6	11.0	4.0
7	15.6	4.6
8	17.6	2.0
9	18.0	0.4
10	18.1	0.1
11	18.2	0.1
12	18.25	0.05
13	18.3	0.05
14	18.35	0.05
15	18.35	0

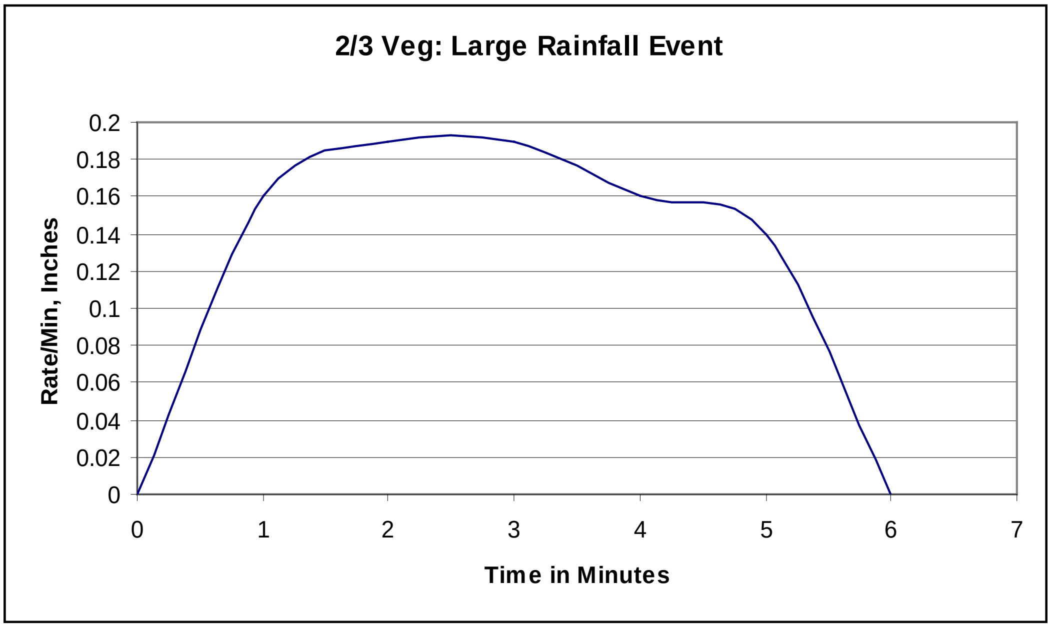

Figure 34: Large rainfall event rate/minute in inches with 2/3 of the rooftops vegetated

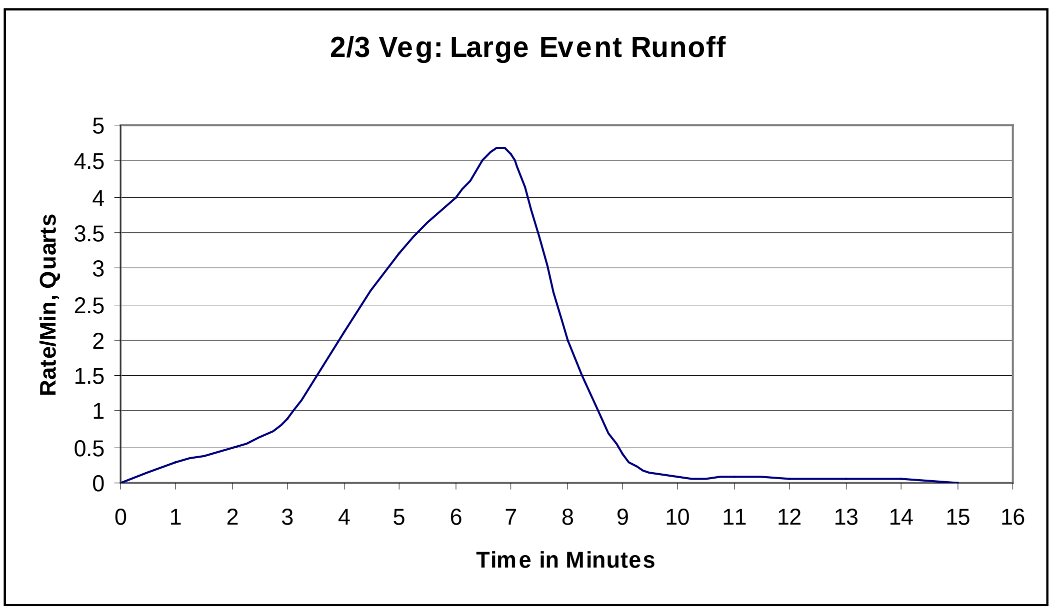

Figure 35: Large event runoff rate/minute in quarts with 2/3 of the rooftops vegetated

CHAPTER 4

ANALYSIS

The variables of interest for this study included 1) the total volume of runoff for each trial, 2) the lag time between peak rainfall and peak runoff, and 3) the duration of runoff response time. Table 19 shows the result of each variable of interest for each size storm event under each rooftop scenario. Figures 36-41 show the rainfall and runoff relationships for each rooftop scenario under each size storm event.

Table 19: Summary of results for each test

	SMALL EVENT			**MEDIUM EVENT**			**LARGE EVENT**		
	Ctrl	**1/3**	**2/3**	**Ctrl**	**1/3**	**2/3**	**Ctrl**	**1/3**	**2/3**
TOTAL RAINFALL (IN)	0.19	0.19	0.2	0.63	0.65	0.62	0.82	0.85	0.84
TOTAL RUNOFF (QT)	5	3.3	2.5	8	6.85	5.4	20.9	20	18.35
LAG TIME (MIN)	5	7	7	4	6	7	4	5	7
DURATION OF RESPONSE (MIN)	8	7	9	8	9	10	9	12	13

The hydrographs for the vegetated roofs produced interesting shapes relative to the control hydrographs. The control hydrographs exhibit steep and steady ascending and descending limbs for each rain event (Figures 37, 39, and 41), while the vegetated hydrographs produce a gradual ascending limb and a rapid descending limb, particularly for the small and medium size rain events (Figures 37 and 39). The shape of the vegetated hydrographs indicates that most of the water retention occurs at the beginning of the storm which corresponds with the

soil reaching field capacity, or saturation, after which, the roof begins to shed the water similar to a conventional roof. The rapidly descending limbs of the hydrographs representing vegetation may suggest that a large percentage of the water is being held, and thus there is a rapid decline in the runoff rate.

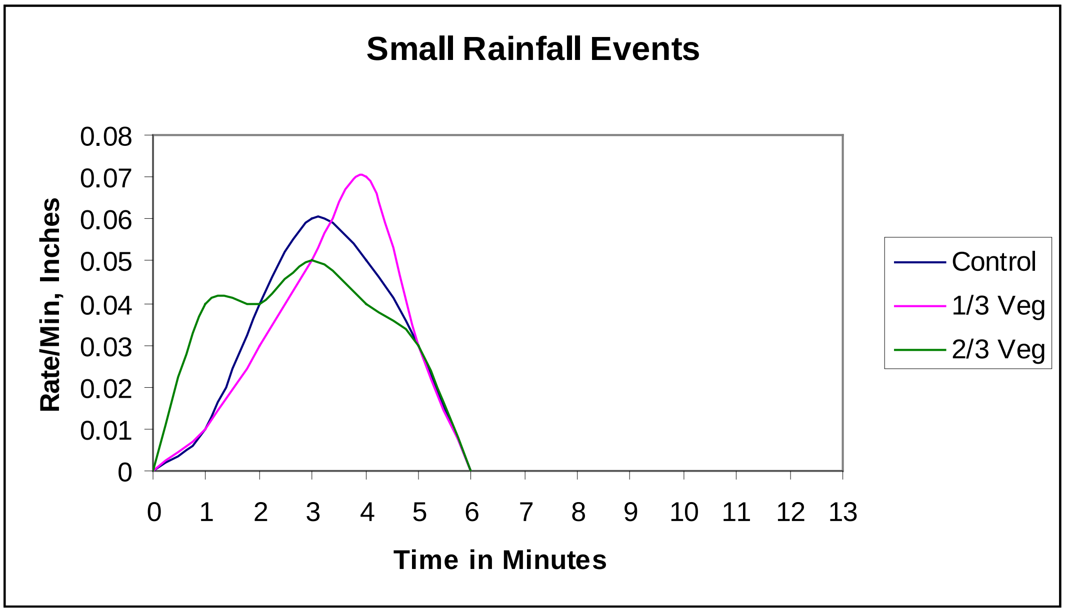

Figure 36: Rainfall rates for each rooftop scenario during the small size storm event

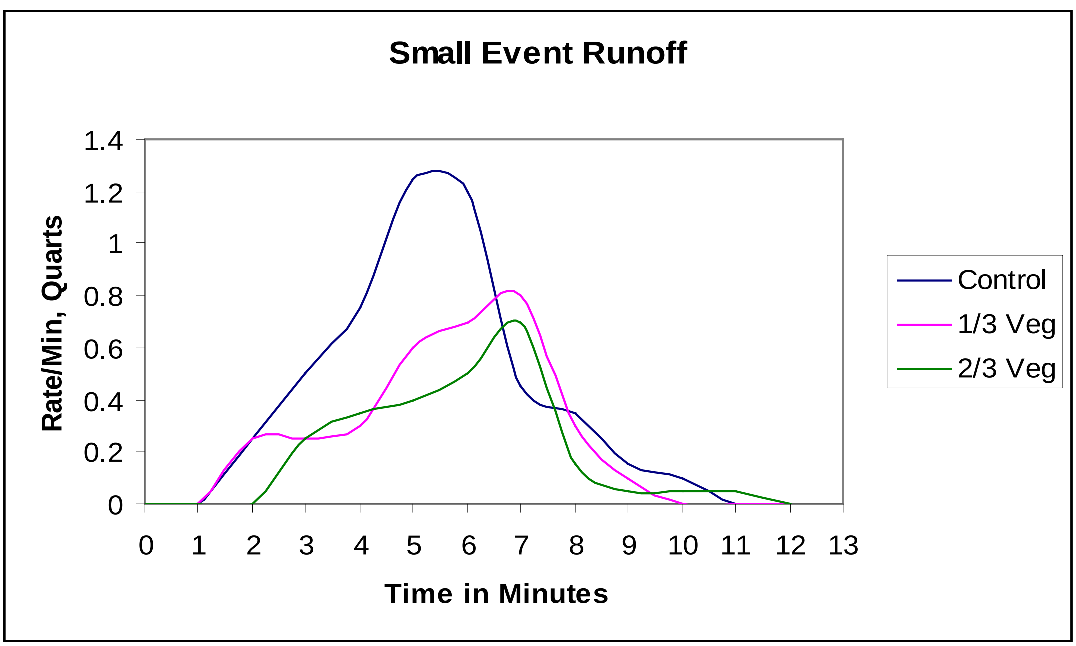

Figure 37: Hydrographs for each rooftop scenario during a small size rainfall event

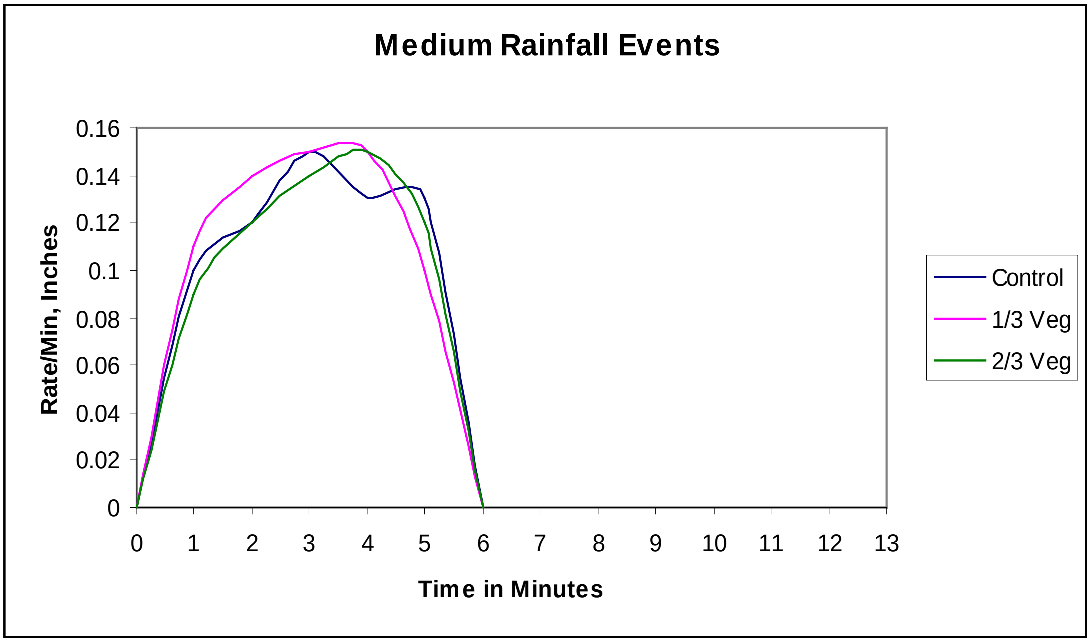

Figure 38: Rainfall rates for each rooftop scenario during the medium size storm event

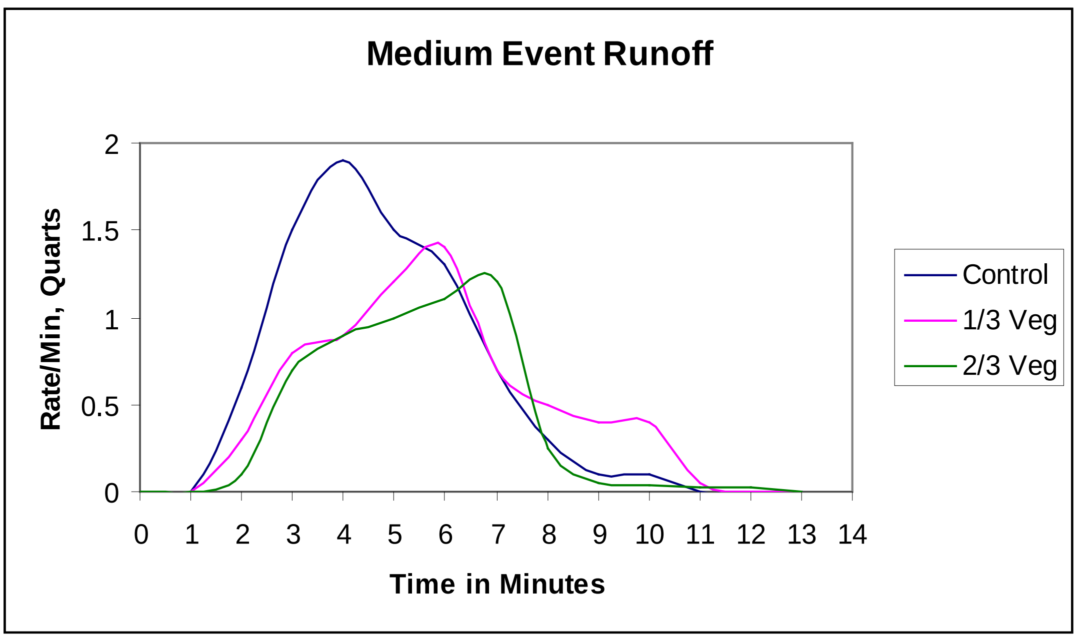

Figure 39: Hydrographs for each rooftop scenario during a medium size rainfall event

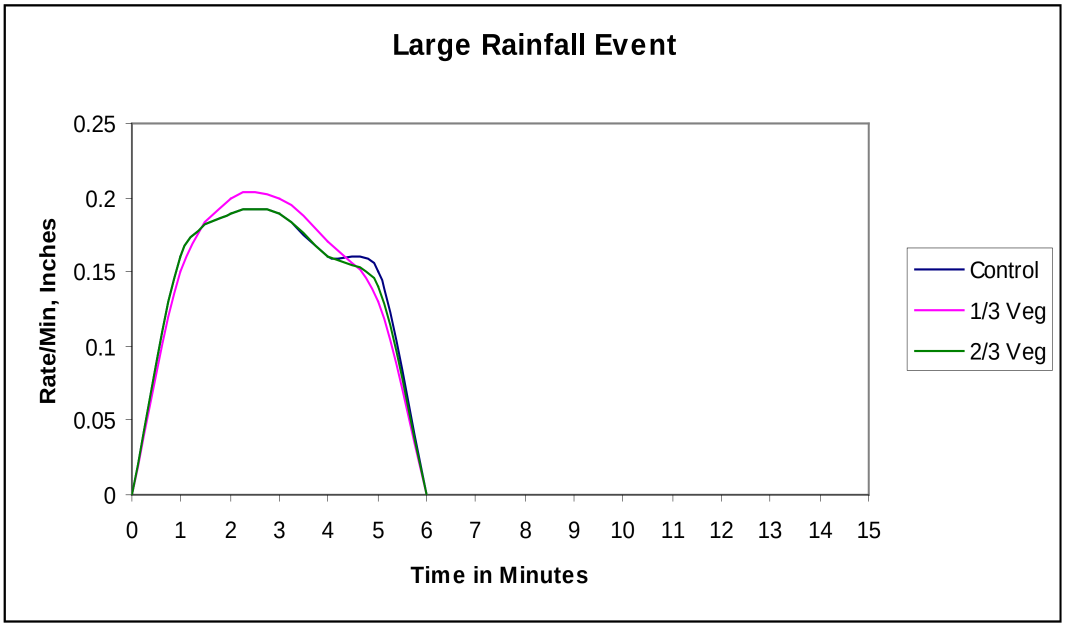

Figure 40: Rainfall rates for each rooftop scenario during the large size storm event

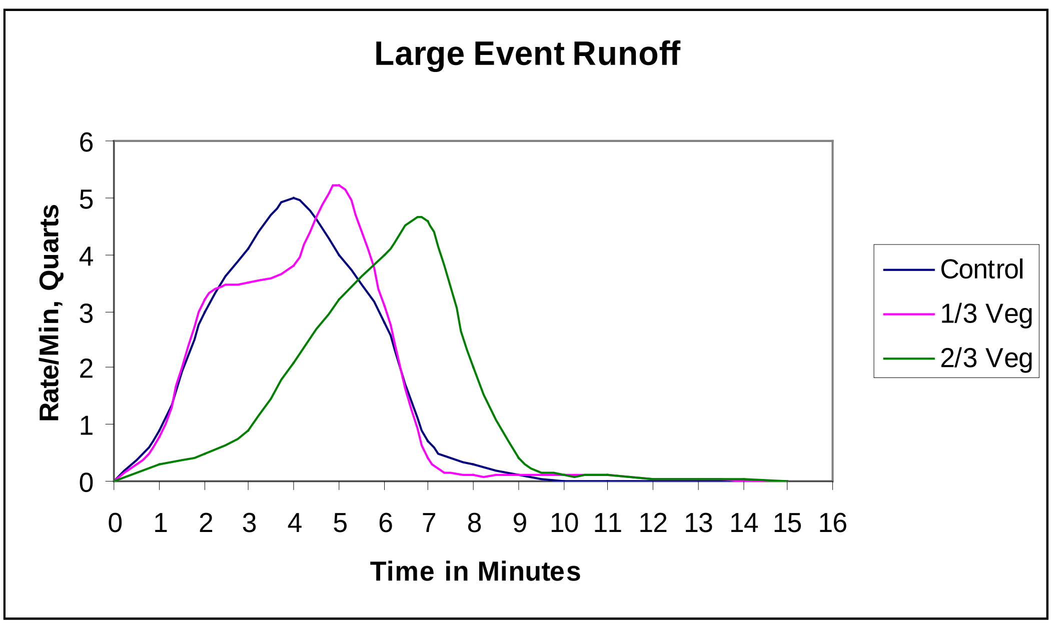

Figure 41: Hydrographs for each rooftop scenario during a large size storm event

These results revealed that as vegetation increased, peak runoff volume decreased, the lag time increased, and in all but one case (the smallest precipitation, 1/3 vegetated model run) the

duration of response time also increased. During the small rainfall event, the peak runoff volume decreased by 34% (from 5qt to 3.3qt) with 1/3 of the roofs vegetated and decreased by 50% (from 5qt to 2.5qt) with 2/3 of the roofs vegetated (Table 19). During the medium rainfall event, the peak runoff volume decreased by 14% and 32% for 1/3 and 2/3 of the roofs vegetated, respectively. During the large rainfall event, the peak runoff volume decreased by 4% and 12% for 1/3 and 2/3 of the roofs vegetated, respectively (Table 19). Therefore, the greatest reduction in total runoff volume occurred during the smallest size storm event, which was consistent with expectations because as storm intensity increases the soil on the roofs became saturated, thereby reducing water retention capacity and resulting in runoff. Thus, there is an inverse relationship between the depth of rainfall and the percent of stormwater retained. Furthermore, for each storm size event, the maximum amount of water retained was approximately 2.5 qt (with 2/3 of the rooftops vegetated), which apparently represents the field capacity of the model. Figure 42 gives the percent reduction in runoff volume for the vegetated rooftop runs relative to the control runs.

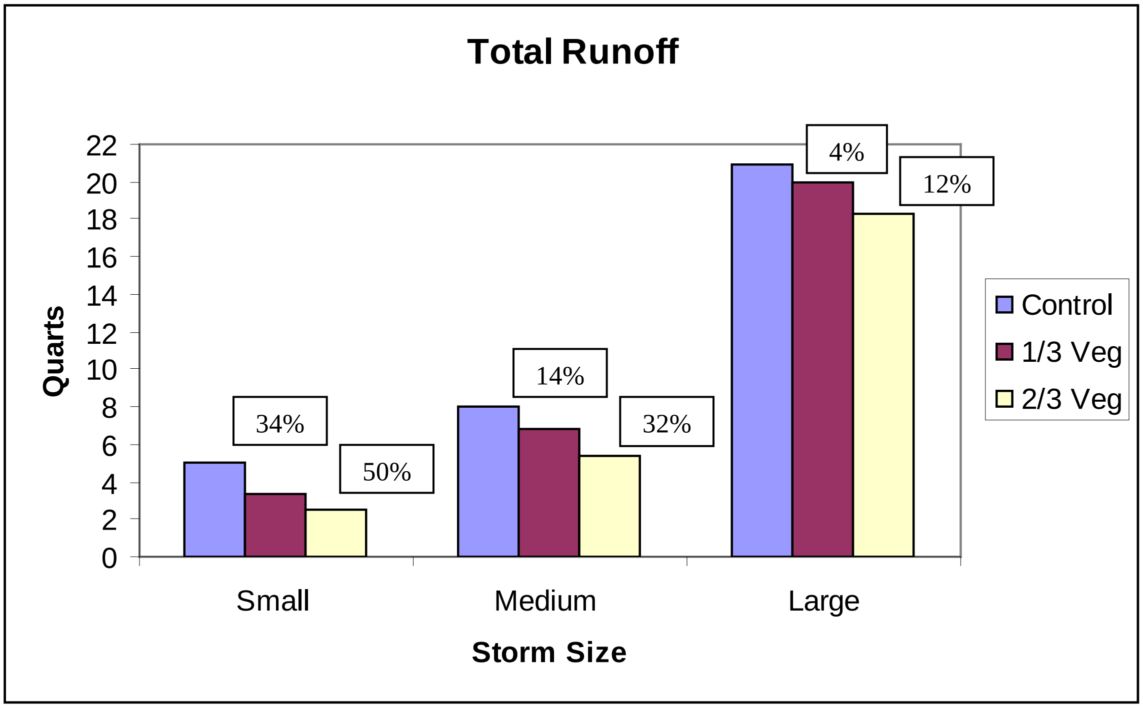

Figure 42: Total runoff for each storm event and rooftop condition with the corresponding percent reduction from the control

The lag time, or time between peak rainfall and peak runoff volume, increased or stayed the same for each storm size as the amount of vegetation increased (Figure 43). The increase in lag time was most substantial for the 2/3 vegetated rooftop runs, extending the total time up to 3 minutes (medium and large events). This result was expected because as the percentage of permeable surface increases the lag time should also increase as a portion of the water is held and thus slows the time it takes for the peak runoff to reach the outlet.

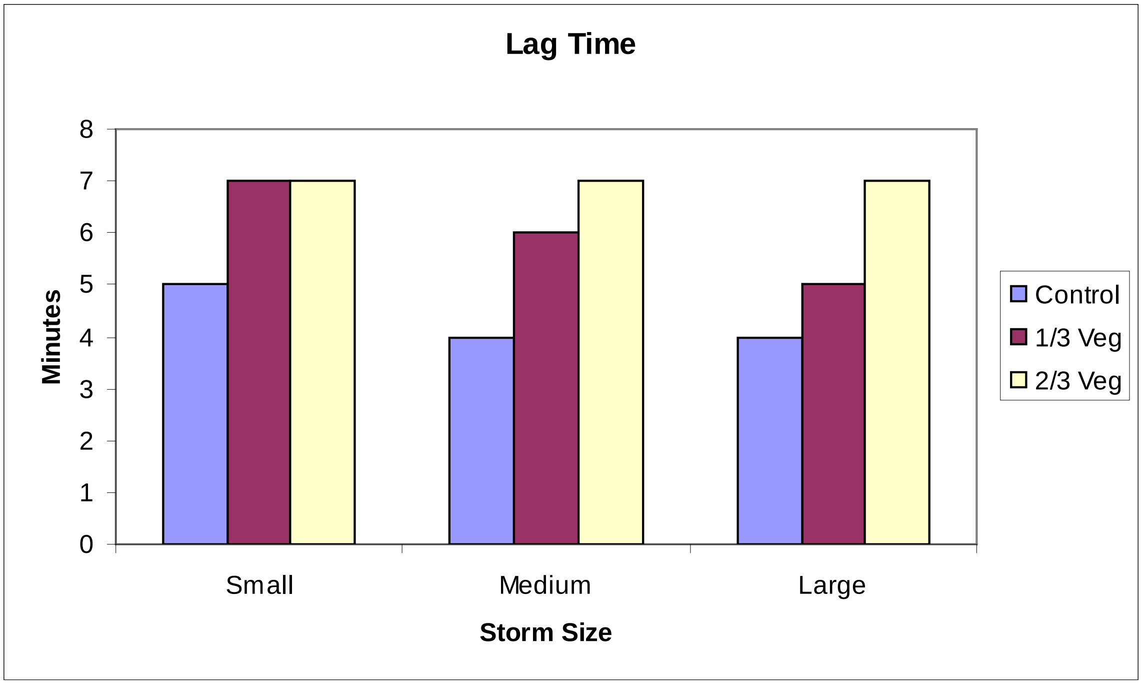

Figure 43: Lag times for each storm event and rooftop condition, the lag time is equal to the time of peak runoff

The duration of response time increased for most of the trials as vegetation was introduced to the model (Figure 44). The only instance where the duration time decreased from the control run was during the small rainfall event with 1/3 of the rooftops vegetated. In this case, the duration time actually decreased by one minute, however, for the small event with 2/3 of the rooftops vegetated, the duration time increased from the control by one minute. This inconsistency could be due to the fact that measurements were only recorded at one minute intervals, giving coarse temporal resolution, or it may have been due to human error. It was expected that durations of response would increase with an increase in vegetation because some of the water was being held by the soil and any excess water did not begin to drain until the soil reached field capacity.

In addition, the spatial pattern of vegetation may have influenced the duration of response times. For the trials with 1/3 of the rooftops vegetated, the vegetation was dispersed relatively

evenly between all three city blocks, so that each had a combination of surfaces. For the trials with 2/3 of the rooftops vegetated, only the city block farthest from the outlet was left with an impervious rooftop, thus potentially slowing the time it took for the building runoff to reach the outlet. This could indicate that it may be more beneficial to vegetate roofs closer to streams because it would slow and reduce the initial amount of runoff entering the receiving water body. However, this hypothesis was not specifically tested during the experiments and is therefore speculative.

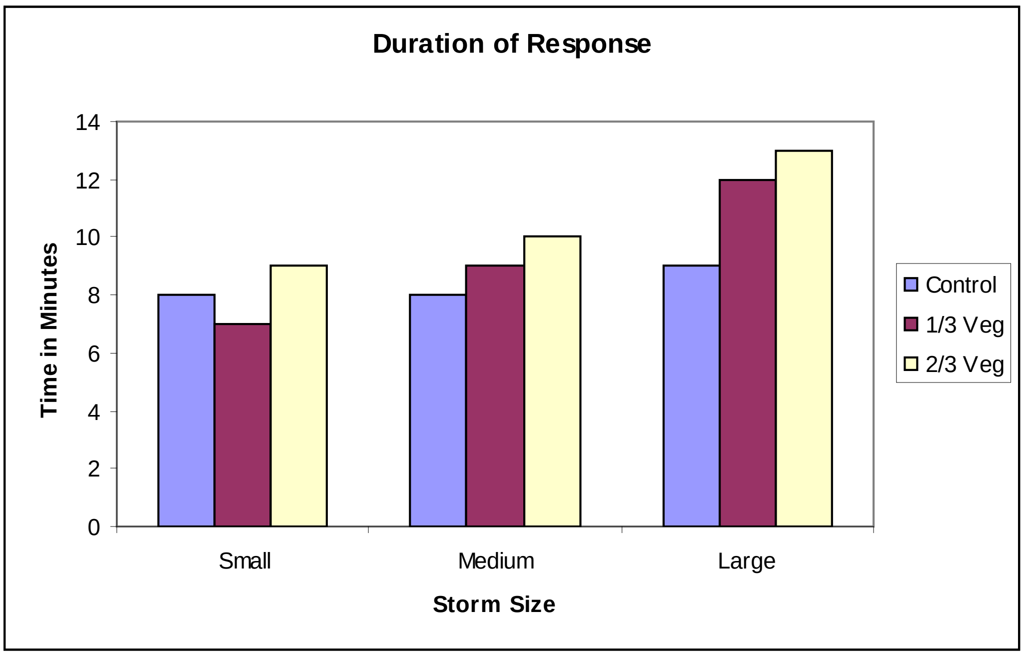

Figure 44: Duration of response for each storm event and rooftop condition, these times represent the significant response time and do not reflect the total duration of the event

There were several complications involved with this study that must be addressed, including the following: (1) the scaling down of the study domain, vegetation, and storm events produced unavoidable inconsistencies, (2) the consistency of rainfall for each rooftop scenario was difficult to control, (3) the runoff collected quickly, making accurate readings difficult at a precision finer than 0.1 quarts, and (4) the structural integrity of the rooftops became

compromised towards the end of the experiments due to their being repeatedly saturated. Additionally, because the model was so large in size and required many tasks to be completed at one time, several people were needed to carry out each experiment, which may have affected measurement consistency. These and other complications are discussed below.

First, the study domain and buildings were modeled at a 1:160 scale and the model rooftops allowed for ½ inch of soil depth, which corresponds to 6.66 ft of soil in the real world. The average real-world green roof only has a depth of 2-10 inches, therefore the vertical thickness of the soil did not scale down perfectly, but it was necessary to provide at least ½ inch of soil so that the alfalfa sprouts could grow and take root. Similarly, the rainfall depths had to be scaled vertically to the soil/vegetation depth, for my model, this gives ratios of 0.5:1, 1:1, and 1.5:1 (rain depth : soil/vegetation depth). This ratio allows one to calculate exactly what real world rainfall intensities per five minutes I have modeled. For example, if a real green roof has a soil depth of 3 inches, using the above ratios the equivalent rainfall depths I tested are 1.5 in, 3 in, and 4.5 in over a five minute period. In the real world these would all be severe precipitation events, however, due to a minimum depth required to grow the sprouts, the vertical scaling could not match the horizontal scaling. Second, although measures were taken to control the amount of “rainfall” for each event, exact consistency was nearly impossible to achieve using the set-up described above. Therefore, the amount of rainfall for each event under the various rooftop scenarios was only approximately the same as the others. Third, while it would have been ideal to collect the runoff in a graduated cylinder marked in milliliters, the runoff overflowed the containers too rapidly, making them impossible to use accurately. Also, the size of the outlet on the model was too large for the size of the graduated cylinders and would have required retrofitting; therefore the 14 quart bucket was used marked in 1 qt increments. Fourth, because

the model buildings were constructed using one inch thick glossy foam board, they eventually started to break down. The siding on some of the rooftops had to be replaced, and mold began to grow in places. Despite some structural degradation, the model buildings were able to survive the duration of the experiments without having to be reconstructed from scratch. However, the original experiment design intended to do a final round of testing with 100 percent of the rooftops vegetated, but due to the partial dilapidation of the structures the final round of tests could not be conducted. Foam board was not the ideal choice for the structures, but due to feasibility issues such as cost and ease of construction, it was the most practical choice. Finally, the experiment was complicated by the need for volunteers to assist with the data collection process. Collection was both delayed and potentially slightly inconsistent due to a number of different people reading and recording measurements. However, multiple model runs were completed for the controls to confidently establish base line conditions. Time limits precluded conducting multiple runs for vegetated roofs because the soil was given a full day to dry out to ensure that antecedent moisture would not interfere with consecutive test runs.

Despite the above mentioned complications, the model proved to be successful at representing conditions found in the real world. Additionally, there was some initial concern that the table-top model would not be able to accurately predict the effects of a real green roof due to their highly technical engineering. However, the main components of a green roof that aid storm water management are the soil and the vegetation, thus the model contained both and was able to work as predicted. Green roofs in the real world have several additional layers for drainage, root barrier, and water sealant that were not a part of this model, however, that did not seem to hinder the results of this study.

CHAPTER 5

CONCLUSIONS

The results of this study revealed that vegetated roofs have the potential to aid in stormwater management in a high-density urban environment. Increased vegetation cover was shown to reduce peak runoff volumes, increase the lag time between peak rainfall and peak runoff, and increase the duration of runoff response. The results indicated that the largest benefits are found during relatively small (but statistically frequent) precipitation events. In addition, the results were more significant when there was a greater percentage of overall vegetation cover.

The metro Atlanta area receives a relatively high annual precipitation of about 48 inches a year, most of which falls as relatively small events (Robbins, 2003). However, the city experiences frequent flooding along urban streams due to large expanses of impervious surfaces as well as aging infrastructure that is designed to combine stormwater runoff with industrial and domestic waste water leading to combined sewer overflows during periods of heavy rainfall (Phillips and Chalmers, 2009). Frequent flooding not only causes problems for property owners, but also leads to disturbances in hydrological, chemical, geomorphic, and ecological natural cycles that occur in streams (Paul and Meyer, 2001). Urban streams tend to have lowered base-flow conditions and flood more frequently than rural streams of the same size under similar conditions (Yin, 1993). The altered hydrologic pattern and increased runoff causes urban streams to have high concentrations of pollutants, especially during times of low flow when there is not enough water to dilute them, but also during rain events when surface water is rapidly delivered to streams carrying high concentrations of non-point source pollution such as oil, pesticides, and fertilizers (Paul and Meyer, 2001). Lower base-flow conditions combined with

frequent flooding alter a stream's geomorphic pattern by causing increased erosion and incision which forces the stream out of a dynamic equilibrium (Bledsoe and Watson, 2001; Nelson, et al. 2006). As hydrologic and geomorphic conditions change, the biologic composition of the stream also changes as sensitive species are replaced by more tolerant species, which leads to a loss of overall species diversity and degradation of stream ecological health (Booth, et al. 2002; Booth, et al. 2004). In order to address these issues, urban stream restoration and planning should be considered at the watershed scale with an emphasis on the percentages of pervious versus impervious surface cover (Ladson, 2004; Wohl, et al. 2005; Bernhardt and Palmer, 2007).

Urban vegetation moderates stormwater runoff and baseflow, underscoring the need to plan and manage urban vegetation (Sanders, 1983). Urban open spaces, all areas that do not contain buildings and impervious surfaces, apparently exert an important influence on the pattern of rainfall-runoff in a city. For example, urban trees in the southeastern U.S. may curtail potential runoff by about 9.6% (Sanders, 1983). Increasing urban development at the expense of open spaces produces long-term costs associated with storm water management. Increasing the amount of vegetation and open spaces in an urban center has the potential to reduce peak runoff flows substantially while at the same time help to reduce the rate of potentially damaging soil erosion (Sanders, 1983).

A great way to bring much needed green space back to urban centers is through vegetated roofs because space is often highly limited as much of the land is already in use; thus it is imperative to look for new ways to use space for multiple purposes. Although green roofs are not a new concept in other parts of the world, such as Germany and other European countries, they offer promising improvements in the United States for providing a sustainably built human environment (Berndtsson, et al. 2005; Van Woert, et al. 2005; Carter and Rasmussen, 2006).

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