Urban to urban-green development: An experimental and modeling study in vegetated roofs for stormwater reduction

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URBAN TO URBAN-GREEN DEVELOPMENT: AN EXPERIMENTAL AND MODELING STUDY IN VEGETATED ROOFS FOR STORMWATER REDUCTION

BY

JAMES A. SHERRARD JR.
B.S. Civil Engineering, University of New Hampshire, 2007

THESIS

Submitted to the University of New Hampshire in Partial Fulfillment of the Requirements for the Degree of

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Date 7/27/10
Dedication

This Thesis is dedicated to my Mother and Father who have always been there for me.

Thank you both for all of your support over the years.
Acknowledgments

I would like to express my thanks to the individuals who contributed to this study. First I want to thank Dr. Jennifer Jacobs who advised me throughout my research and kept it all on track. Her experience and knowledge was invaluable over my time working with her and without her help this research would not have been possible.

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ABSTRACT

URBAN TO URBAN-GREEN DEVELOPMENT: AN EXPERIMENTAL AND MODELING STUDY IN VEGETATED ROOFS FOR STORMWATER REDUCTION

By

James A. Sherrard Jr.

University of New Hampshire, September, 2010

The incorporation of vegetated roofs into a region’s stormwater management plan may be an efficient method of managing flooding issues and combined sewer outflow system maximum loads. Currently, vegetated roofs are not widely used within New England as a common stormwater Best Management Practice. My research explores vegetated roof stormwater retention performance in the Seacoast New Hampshire region. This research experimentally quantified the complete water balance of a vegetated roof system in an outdoor, rooftop setting, developed a predictive vegetated roof stormwater retention model and modeled retention for an eight year period from 2002 to 2009. This eight year model was applied to downtown Portsmouth, NH by identifying the roof top area potentially capable of supporting vegetated roofs and quantifying the volumetric stormwater reduction.
Chapter 1 – Introduction

1.1 Background/Literature Review

1.1.1 Why is this Problem Important

Stormwater, while generally viewed in an urban context, is broadly defined as the total overland flow generated by a precipitation event. In natural landscapes, such as forests, fields, and wetlands, precipitation infiltrates into pervious surfaces at varying rates. In urban settings, pervious surfaces are replaced by impervious surfaces, such as rooftops, roadways, and sidewalks. This increases the stormwater volume and peakflow, and decreases the runoff start time. A typical city block creates five times more runoff than a woodland area of the same size, due to impervious surfaces (EPA 2003). Stormwater can transport petroleum based products, sediments, fertilizers, and chemical products commonly found on impervious surfaces (Peters 2009). Stormwater, ultimately draining to streams, lakes, and rivers, causes elevated levels of these pollutants (Peters 2009). While human water use can impact hydrologic systems (Weiskel et al. 2007), in general the dominant factor altering hydrology is urbanization (Claessens et al. 2006). Therefore, reducing stormwater is necessary to reduce urbanization effects on the water cycle.

There are many stormwater Best Management Practices (BMPs) that can efficiently reduce stormwater impacts. When implementing a stormwater BMP, it is
important that the strengths and weaknesses of the available options are considered. For a particular scenario it may be necessary to replace lost evapotranspiration, recharge groundwater, reduce total runoff volumes, protect stream channels, control peak runoff rates, or reduce pollutant loads (DES 2008).

Stormwater BMPs, which are designed to retain and sometimes reduce stormwater before entering urban waterways (Carter and Rasmussen 2006), are broken into two main categories; pre-treatment and treatment. Pre-treatment stormwater controls include sediment forebays, vegetated filter strips, pre-treatment swales, and flow through devices. Treatment BMPs include; stormwater ponds/wetlands, infiltration trenches/basins/wells, underground and surface filters, bioretention systems, tree box filters, permeable pavements, swales, and buffers (DES 2008). Because many stormwater BMPs require large areas, it is difficult to incorporate these systems into urban areas post-construction. In addition to space availability, many BMPs are chosen based on current land use, public perceptions, funding, and aesthetics (Villarreal and Bengtsson 2004).

Vegetated roofs are in a unique position to reduce stormwater loads within highly urbanized areas because they are able to re-inhabit previously unutilized rooftop space. This is a desirable trait for urban centers which have little additional space to reduce stormwater loading and infrastructure that is unable to handle increased loads due to urbanization. In some highly urbanized areas rooftops can constitute from 30 – 50% of the impervious surface (Dunnett and Kingsbury 2004; Carter and Rasmussen 2006; Oberndorfer et al. 2007).
Vegetated roofs are similar to bioretention BMPs in that they utilize both a soil medium and vegetation to reduce stormwater. However, bioretention systems tend to be much larger, utilize ground level space and have a larger variety of vegetation coupled with traditional soils. When utilized as a BMP, vegetated roofs have been shown to reduce stormwater inputs by up to 49 mm/year through evapotranspiration (Mitchell et al. 2008). In some studies, vegetated roofs have decreased roof runoff volume by 70% more than a conventional ballasted roof (Bliss et al. 2009) and reduced overall runoff from conventional urban layouts by 18% (Mitchell et al. 2008). Vegetated roofs may not sufficiently reduce stormwater loads in all urban situations. However, when used in conjunction with other stormwater BMPs, an acceptable reduction may be obtained.

In addition to stormwater reduction, vegetated roofs can provide an array of benefits to an urban area as well improve aesthetic appeal. Increase energy efficiency within buildings including up to a 40% reduction in cooling loads for summer months (Spala et al. 2008), Double the life of a traditional roof up to 40 years (Carter and Keeler 2008). Decrease the ambient air temperature; for example a 25°C average decrease on the Chicago City Hall roof (Yocca 2003). Provide enhanced habitat such as nesting birds and the re-introduction of rare plants and lichens (Oberndorfer et al. 2007). Reduce noise pollution by up to 10dB when compared to an acoustically rigid roof (Van Renterghem and Botteldooren 2008). Provide a buffer from acid rain (Berghage et al. 2007; Berndtsson et al. 2008). Shorten patient recovery times in hospitals (Ulrich 1984).

Vegetated roofs, which are sometimes referred to as green roofs, consist of a soil medium and plants placed on top of a structure. Traditionally there are two types of vegetated roofs, intensive and extensive. Intensive roofs, whose name reflects the
intensive amount of effort required to maintain them, have deep substrate depths and tend to be used for agriculture or aesthetic reasons. Extensive roofs, have a much shallower soil medium. They require less maintenance and have lower costs than an intensive roof. Soil depths of intensive roofs typically are at least 15 to 20 cm thick (Getter and Rowe 2006; Oberndorfer et al. 2007). Maximum thickness is limited only by the structural integrity of the building and of the occupants’ ability to maintain such a roof. Extensive vegetated roofs typically are either modular or plant-in-place systems. Modular systems are self contained containers that can be moved as individual units while plant-in-place systems are homogeneous throughout the roof with no vertical dividers.

When vegetated roofs are built into the building plan, the weight bearing capacity can be adjusted prior to construction to account for the weight. When added post-construction, the additional load from vegetated roofs must be considered. Generally, extensive roofs will increase the load on a roof from 70 to 170 kg $m^{-2}$ (14 to 35 lb $ft^{-2}$) while intensive roofs increase the weight from 290 to 970 kg $m^{-2}$ (59 to 199 lb $ft^{-2}$) (Dunnett and Kingsbury 2004). Weight depends on substrate depth and vegetation. Buildings need to be examined individually to determine if there is a need for additional structural support. Also, building roof capacity varies by region. In areas with consistent snow loads, like New England, the design for these loads coupled with the factor of safety may be sufficient to support a vegetated roof. It is important to consider each building’s load capabilities and the loading standards for the region in which it is located in prior to installation of a vegetated roof.
Extensive roofs are typically no deeper than 20 cm. The shallowest systems' thickness is constrained only by the plant requirement. Visually, extensive systems are quite different than intensive roofs. Intensive roofs often mimic parks or gardens and essentially augment green space in urban settings (Oberndorfer et al. 2007). Extensive roofs are also green but typically have drought tolerant and hardy succulent species such as sedums which will rarely grow to heights more than 20 cm (Getter and Rowe 2006). While each roofing type has its own benefits and limitations, extensive roofs are a practical option for stormwater management. The remainder of the section focuses predominantly on extensive roofs.

1.1.2 Early Research Through Present

Vegetated roofs have been used for thousands of years in various fashions and cultures. Dating back to 500 B.C, the hanging gardens in Babylon are a well known example of a vegetated roof (Getter and Rowe 2006; Oberndorfer et al. 2007). These roofs were used through the Renaissance and Middle Ages as roof gardens for the rich, and eventually found more practical uses as insulative roof cover for Norwegians through the 15th and 19th centuries. While vegetated roofs have a long history, Germany is given credit for pioneering the modern-day vegetative roof around the turn of the 20th century (Oberndorfer et al. 2007) and since then Germany has used vegetated roofs extensively. By 2005, vegetated roofs covered 14% of its flat rooftops (Getter and Rowe 2006). Ordinances in some German cities require all new, flat-roofed construction to have vegetated roofing.
Vegetated roofs are being increasingly used in the United States (Thompson 2000) with cities such as Chicago, Portland, Atlanta, and New York utilizing vegetated roofs for stormwater control and food production (Getter and Rowe 2006). While much of the European vegetated roof use was implemented for aesthetics, insulation, or as a fire retardant (Getter and Rowe 2006; Oberndorfer et al. 2007), controlling stormwater is a leading reason for their use in North America. Studies have investigated vegetated roofs impacts on water quality. However, my research focuses on water quantity rather than water quality.

Researchers have found that vegetated roofs typically reduce overall stormwater volumes, and peak flow runoff. An Estonian study comparing a 100 mm vegetated roof deep to a bituminous membrane reference roof showed an average stormwater reduction of 88% for 2 light rainfall events (2 mm) and no overall reduction for a single heavy event (18 mm) (Teemusk and Mander 2007). A Pennsylvanian study of thirteen storms over 5 months also compared a vegetated roof to a ballasted membrane control roof (Bliss et al. 2009). They measured a volumetric percent reduction of 67% for storms under 6 mm, 23% for storms between 6 and 20 mm, 19% for storms between 20 and 40 mm, and 10% for storms between 40 and 56 mm. Two separate comparative studies were performed in North Carolina. Runoff from a vegetated roof with an average substrate depth of 75 mm was compared to a gravel ballast control roof and a conventional non-ballast control roof at a 3% pitch (Hathaway et al. 2008). The vegetated roof reduced runoff volume by 77 and 88%, for the ballast and non-ballast roofs, respectively. The vegetated roofs retained 64% of the total rainfall.
Roof slope can affect water retention capabilities. In Michigan, researchers compared runoff from a vegetated roof with a 60 mm substrate depth for slopes of 2, 7, 15, and 25% (Getter et al. 2007). Their 2 year study results were summarized by three rain categories; light (less than 2 mm), medium (2 – 10 mm) and heavy (greater than 10 mm). The rainfall retention for the 2% slope over the light, medium and heavy events was 93, 92, and 71%, respectively. For the extreme 25% slope, 95, 88, and 57% of the events were retained for light, medium, and heavy rainfall, respectively. This suggests that steeper slopes are less able to retain stormwater with increasing rainfall depth. A separate Michigan study conducted two comparative experiments on vegetated roofs (VanWoert et al. 2005). The first study compared the retention capabilities among a gravel ballast roof, an extensive roof without vegetation, and an extensive roof with vegetation. The second study compared the effect of varying slopes (2 and 6.5%) on vegetated roofs with substrate depths of 25, 40, and 60 mm. For all rainfall events, gravel, solely substrate, and vegetated roofs showed overall reductions of 27, 50, and 60%, respectfully. The 2% slope (with the 6.4 and 10.2 mm substrate depths) showed an overall average reduction of 70%. The 6.5% slope (with the 40 and 60 mm substrate depths) obtained overall average reductions of 67%. Again, no appreciable performance differences occurred with slopped roofs under light and medium events. Only under steeper slopes and heavy events do retention capabilities diminish.

In summary, stormwater control percentages can vary widely. Most of the studies measured precipitation and drainage from the vegetated roof. Reductions vary among studies and may be attributed to the differences in the substrate depth, substrate composition, and extent of plant propagation for each study roof. In addition, auxiliary
aspects such as climates, roof slope, height, and surrounding buildings all may affect results. There are, however, general trends that have been discovered for vegetated roofs. Differences among the media storage based on the substrate depth, soil properties, storm depths and frequencies, and a variation of plant species make it difficult to transfer results while comparing runoff retention results.

Water storage within vegetated roofs primarily depends on the water loss due to evapotranspiration (ET) between storm events. This function differentiates vegetated roofs from other existing storage and retention methods. However, few studies have examined the loss of water due to ET from roofs and the resulting evolution of storage between rainfall events.

A 2003 study from Oxfordshire, UK showed that flat un-vegetated roofs can achieve a evaporation to rainfall ratio of up to 38% (Ragab et al. 2003). For their one year study period, this is approximately 0.65 mm/day of evaporation. This is likely an upper bound because the study roofs encouraged ponding and were constructed using bitumen coverings with felt and chippings. Few rooftops will match these attributes since construction techniques typically encourage rapid drainage from rooftops. A model which used this 2003 data set predicted that 40% of storm events would be removed through evaporation alone (Gash et al. 2008). Due to the inconsistencies in data collection for the 2003 study, it is likely these numbers also overestimate the capability of rooftops to evaporate stormwater.

A 2005 study conducted in North east Italy estimated evapotranspiration rates and monitored the thermal flux within a vegetated roof (Lazzarin et al. 2005). Temperatures were gathered at varying depths within the module and on the surface to acquire the
thermal fluxes. Estimated ET data were used with a Penman-Monteith model to obtain crop coefficients. ET rates estimated from figures in the paper appear to range from 0.69 to 6.9 mm/day with typical values of 1.6 mm/day. This residual term, ET, includes all errors. While this is a reasonable approach, it is not a direct measurement of water loss due to ET.

A Canadian study, examining individual plant species water use, showed varying ET rates by soil saturation level (Wolf and Lundholm 2008). Their greenhouse controlled watering to maintain wet, intermediate, and dry conditions yielded 1.7, 1.3, and 0.5 mm/day of ET, respectively, from succulents. A Pennsylvania greenhouse study used lysimeters to determine evapotranspiration rates from vegetated roof modules (Berghage et al. 2007). Modules were planted with three different types of vegetation (Sedum spurium, Delosperma nubigenum, and Sedum album). Two and ten days after watering yielded average ET rates of 1.9 and 0.4 mm/day respectfully. Observations of ET rates provide researcher’s ways to characterize vegetated roofs. These characterizations, in order to be of benefit, must be modeled to ascertain effectiveness and practicality of use in urban areas.

Relatively few vegetated roof models exist. Most models focus on runoff predictions and many models modify an existing framework for vegetated roof parameters. Some models are empirical with coefficients for vegetated roofs using methods such as the curve number (CN) method and the unit hydrograph method (Villarreal and Bengtsson 2005; Carter and Rasmussen 2006). Villareal and Bengtsson (2005) used linear programming techniques to create unit hydrographs (UH) for vegetated roofs. The UHs were used to predict peak flows and runoff from individual
events. Their volumetric reduction predictions, when compared to observed results, averaged 0.3 mm higher with some differences for larger events. Using a black roof and vegetated roof comparison, Carter and Rasmussen's (2006) calibration approach found a CN of 86 using the Soil Conservation Service Method (SCS Method). rooftops, as impervious areas, are generally assigned CN numbers of 98. A CN of 86 is comparable to lawns and parks with less than 50% grass cover in hydrologic soil group C (Maidment 1993). The CN of 86 was not validated independently. The SCS method, which was originally created as a tool to estimate floods on small to medium-sized drainage basis (Maidment 1993), was not created for rooftops and was intended for design rainfall events. Thus it may not be the best approach to quantify vegetated roof retention characteristics. In addition, while the empirical approaches can predict runoff from vegetated roofs, they lack the ability to capture differences among roofs and to explain the drivers of stormwater reduction.

Energy balance models of vegetated roofs have been more successful at capturing the roof physics. Lazzarin et al. (2005) created a predictive numerical model which calculates multi-nodular energy fluxes. Their approach used soil properties and atmospheric conditions to drive the model. When compared to ET measurement results, their correlations were good for one dataset and poor for another. Another energy balance model was applied to a 24 km² urbanized catchment with multiple stormwater BMPs including vegetated roofs (Mitchell et al. 2008). While their model was based on a surface energy balance equation, the soil profile characterization was less detailed and runoff was estimated indirectly. Their study results were calibrated using a previous study, but not validated or compared to measured values.
A water balance is the most commonly used modeling approach for vegetated roofs. The SWMS_2D model, which is governed by Richards' law and Van Genuchten-Mualem functions, was applied to a vegetated roof to model the vertical saturation profile (Palla et al. 2009). With a soil profile similar to Lazzarin et al. (2005), this multi-nodular approach has the capability of capturing details in vegetated roofs. Palla et al. (2009) calibrated and validated their model with eight rainfall events for each and compared predicted and measured outflow. Their model showed relative percent deviations, from actual stormwater runoff volume, from 1 to 33% and from 0 to 35% for estimating peak runoff.

A similar model, HYDRUS-1D, was used to model peak flow and runoff retention and detention times for 24-hr design storms (Hilten et al. 2008). This model estimates ET using the Hargreaves and Samani method and infiltrates water using Richard's equation with soil parameters determined using the Van Genuchten soil hydraulic functions. The HYDRUS-1D model requires precipitation, potential evapotranspiration, and soil properties including field capacity, wilting point, density, and soil type. Hilten et al.'s (2008) simulated and observed runoff values were well correlated ($R^2 = 0.92$) with errors increasing as runoff increased.

Other models have used a simpler bucket approach to conduct the water balance and simulate module storage where water drains once storage capacity is exceeded. Berghage et al. (2007) created separate annual and storm event models to estimate stormwater runoff for vegetated roofs. Their Annual Green Roof Response Model (AGRR) predicts the annual roof runoff on a daily time step and uses daily precipitation and evapotranspiration values. Their event model, the Storm Green Roof Response
Model (SGRR), is a modified Puls Reservoir Routing model. The SGRR requires a storm hyetograph, ET and the month in which the storm occurred. The SGRR's limited storm basis provides a useful tool to analyze a single event, but it is unable to represent retention capabilities over longer periods. In addition, the storage capacity of the vegetated roof is estimated by the number of days since the previous event. The SGRR model compared well to observed data ($R^2 = 0.91$) with the best performance for rainfall events less than 21 mm.

Appropriate models are useful for understanding the effects of individual vegetated roofs as well as their potential effectiveness in reducing stormwater for municipalities. While research has been conducted on relatively small test plots, some researchers have applied those results to larger municipal and watershed based scales. Mitchell et al. (2008) modeled stormwater runoff reduction in a 24 km² Australian suburban catchment using Aquacycle, an urban water balance model. Stormwater runoff was reduced 49 mm over one year by replacing all impervious roofs with vegetated roofs.

Villarreal et al. (2004) conducted an experiment on a 49,000 m² inner city suburb in Sweden. This suburb has different types of BMPs including swales, gardens, channels, wetlands, wet ponds, dry ponds, ponds, and vegetated roofs. Using synthetic hydrographs and an estimation of the runoff flow into each system was obtained, then routed through each system using PondPack, a surface stormwater modeling program. Within this municipality, vegetated roofs were found to reduce stormwater runoff by 34, 24, 21, and 15% for storms with return periods of 0.5, 2, 5, and 10 years respectively. When used in conjunction with the additional BMPs, a stormwater runoff reduction of 79 mm was modeled for this municipality over the course of a year.
Carter and Jackson (2007) modeled a 237 ha watershed in Georgia, which encompasses the majority of the University of Georgia and the urban center of Athens. Assuming that all rooftop surfaces were covered with vegetated roofing and utilizing a CN number of 86 (Carter and Rasmussen 2006), their model predicted 37, 17, 8, and 3% reduction from 1.3, 3, 8, and 20 cm design storms in the study area.

1.1.3 Research Needs

While experimental studies in vegetated roof stormwater retention have quantified the general characteristics of rainfall-runoff relationships, little is known about the storage evolution between and during events. In order to understand the drivers, studies must take into account time between events and, accordingly, the soil moisture content at the beginning of each event. Ideally, atmospheric conditions such as temperature, wind speeds, and solar radiation should be used to estimate the evapotranspiration rates from vegetated roofs. Two studies having the best ET and storage data were performed with greenhouses (Berghage et al. 2007; Wolf and Lundholm 2008). Because the vegetated roof was not exposed to the exterior environment, it is difficult to transfer greenhouse conditions and results to a rooftop setting. In addition, Berghage et al.’s (2007) watering technique in the greenhouse studies was to repeatedly saturate and drain the vegetated roof prior to monitoring the ET. These conditions are not comparable to naturally occurring wetting and drying. With a more in-depth monitoring study, a better understanding of vegetated roof water dynamics will be possible.

Ultimately, the monitoring studies should be used to develop models. A reasonable model must be robust enough to be applicable at different sites and for
different module media. However, they can not require more parameters and input data than are readily available from standard engineering practice. Existing hydrologic models created or altered to characterize vegetated roof water and energy dynamics vary in complexity and versatility. While empirical hydrologic models with coefficients for vegetated roof characteristics are useful, their original purpose was for a larger scale then a single rooftop and, as before, the model is not transferable to other sites. As for the multi-nodular studies e.g., (Lazzarin et al. 2005; Palla et al. 2009), these studies are, perhaps, overly parameterized and cumbersome for a system with substrates depths of 10 cm or less. Berghage et al. (2007) strikes a reasonable balance through their use of a physically-based water balance and simplified processes. Ultimately a set of standard values will be required to compare and model vegetated roofing systems. These values should readily available or easily measured as well as transferable among models and valid for different time steps.

1.2 Research Objective

The goal of this research is to experimentally quantify the complete water balance of a modular vegetated roof system in an outdoor, rooftop setting. In short, a roof. Since the available storage is an important factor in vegetated roof stormwater reduction, a high-resolution lysimeter experiment similar to the reviewed greenhouse studies was conducted to obtain detailed observations of water inputs to and outputs from a vegetated roof.

To date the only similar experiments have been conducted either in protected areas (e.g. greenhouses) or, when exposed, have made observations that require ET to be
inferred rather than measured directly. This research seeks to better understand how soil water losses to evapotranspiration affect storage capabilities and runoff within a vegetated roof. My research objectives are to: 1) design a lysimeter system to monitor module water storage change over time, 2) experimentally determine the water balance components of a vegetated roof system including precipitation, runoff, evapotranspiration, and storage, 3) develop a model which can predict vegetated roof water dynamics over multiple months, and 4) apply the model at a regional scale.

A greater understanding of water storage within a single module can be translated to other locations and larger scales that are relevant for stormwater management. Practically, the research is posed to provide input for stormwater management.
Chapter 2 - Experiment Description

2.1 Kingsbury Roof/Morse Roof

2.1.1 Research Site Description

The research site is located on the roof of Kingsbury Hall at the University of New Hampshire in Durham, New Hampshire (Figure 2-1). An aerial photograph of the site is provided in Figure 2-2. The site is located approximately 12 km from the Atlantic Ocean and has similar weather patterns to the coastal city of Portsmouth, NH. Kingsbury Hall is an academic and research building that was newly renovated in 2008. Kingsbury Hall hosts the mathematics, civil, mechanical, electrical, and chemical engineering departments.
Figure 2-1: State of New Hampshire with experimental site location Durham (Blue) and modeled site Portsmouth (Red)
Figure 2-2: Aerial view of Kingsbury Hall (circled in red) and Morse Hall (circled in blue).

The area surrounding Kingsbury Hall has a local building density of 68 buildings/km² (Figure 2-3). In the immediate surroundings, Kingsbury Hall is bordered by a dining hall, academic buildings, and dormitories with varying distances including Parsons/Iddles Hall (25 m), Paul Creative Arts Center (30.5 m), Morse Hall (15 m), Spaulding Hall (36.5 m), Philbricks Dining hall (137 m), the Southeastern Residential Community (77 m, 122 m, 305 m respectively), and Forest Park (46 m).
The Kingsbury Hall roof is an open expanse of light grey roofing material approximately 29 and 33.5 m to the West and East sides, respectfully. The North (Figure 2-4) and South (Figure 2-5) facing sides are approximately 27.5 m wide. A site plan layout is provided in Figure 2-6. The roof section used for the experiment is located at latitude 43.1341°N and longitude 70.9348°W, and is approximately 30 m above sea level and roughly 10 m above the ground level.
Figure 2-4: North facing wall on Kingsbury Hall.

Figure 2-5: South facing wall on Kingsbury Hall.
Figure 2-6: Kingsbury roof layout (Courtesy of the University of New Hampshire Plan Room). Site bordered in red.

The North and South facing walls are 6 and 4.7 m tall, respectively, and extend the width of the roof (Figure 2-7). On the East and West sides, the roof has an unprotected edge above a loading dock and center courtyard (Figure 2-8 and Figure 2-9).
Figure 2-7: North and south facing walls, roof elevation layout (Courtesy of the University of New Hampshire Plan Room). Site highlighted in red.
Figure 2-8: West facing roof edge on Kingsbury Hall.

Figure 2-9: East facing roof edge on Kingsbury Hall.
2.1.2 Portsmouth Site Description

Portsmouth, NH is located approximately 14 km from the research site in southeastern NH at latitude 43.0764°N and longitude 70.7569°W (Figure 2-1). The site, shown in an aerial photograph in Figure 2-10, is located in the downtown area which boarders the Piscataqua river. The Portsmouth site, which is approximately 340,000 m², was selected by the City of Portsmouth because it is an area of high building density and historical stormwater management issues (Figure 2-11).

Figure 2-10: Aerial view of Portsmouth, NH.
Figure 2-11: Portsmouth downtown study site highlighted in blue including buildings (light blue) and roads.
2.1.3 Module Frame

The first research goal was to develop a system to monitor the vegetated roof’s water storage over time. My system uses a weighing approach in which the vegetated roof module is suspended from a frame structure. The module frame was designed to provide adequate clearance for a 100 kg minimum load capacity. The frame also was designed to withstand the effects of weathering, wind, rain, ultraviolet rays, and freezing temperatures. Finally, the design is easily assembled on a roof with limited access.

The system's frame is constructed from 1.9 cm galvanized steel pipes (Figure 2-12). The pipe is jointed together with galvanized steel T, 45° bends, close nipple (Figure 2-13), and 90° bend connections (Figure 2-14). A galvanized steel 56 kg test wire is used as both horizontal and cross supports in tension. The rope reel is threaded into the support frame (Figure 2-14) and connected in the center by a turnbuckle to facilitate tightening (Figure 2-15). The steel wire is threaded underneath steel C channel supports (Figure 2-16) and both ends are connected to the split ring hanger. Two split ring hangers are connected above and below the load cell and connect to both the module frame and the hanging module. These hangers connect to an overhead horizontal pipe which supports the entire module and its steel supports (Figure 2-17). The frame is placed on specialized concrete blocks with a protective undercoating to minimize damage to the roofing material. These concrete contact points also act as a friction surface to reduce horizontal movement due to wind.
Figure 2-12: Galvanized pipe frame on Kingsbury Hall.

Figure 2-13: T, 45°, and close nipple connectors on Kingsbury Hall.
Figure 2-14: 90° Connector and galvanized steel wire threaded into module support on Kingsbury Hall. Module support resting on concrete blocks with protective undercoating.

Figure 2-15: Galvanized steel wire in cross and horizontal tension on Kingsbury Hall.
Figure 2-16: Steel C channel supports under the module on Kingsbury Hall.

Figure 2-17: Split ring hangers attaching to metal wire and load cell on the bottom side and the load cell to the module frame on the top side. Located on Kingsbury Hall.
2.1.4 Module

The modular system for this study was provided by Weston Solutions, Inc. through the UNH Cooperative Extension. This experiment used Green Grid ® modular vegetated roofs, which were first cultivated in 2007 that were pre-planted prior to installation. Typically a geotextile is placed between the roof and the growing medium or module to prevent plant roots from damaging the roof of the structure. Because the modules were suspended slightly above the roof, no membrane was installed.

For this experiment, I used two 1.22 (4) by 0.62 m (2 ft) modules made of recycled plastic. These modules have a 25 mm (1 in) lip on the upper outer edge to facilitate transportation. They are approximately 100 mm (4 in) in depth and hold that equivalent depth of substrate. Retention areas, 89 mm² (3.5 in²) and 13 mm (0.5 in) deep, are located on the bottom of the module and store water without drainage. The remainder of the bottom of the module has channels running the length and width of the entire module with drainage perforations spaced intermittently. Drawings provided by Weston Solutions Inc. show an aerial and side view of the research module (Figure 2-18 and Figure 2-19).
Figure 2-18: Aerial view of research module (Figure Courtesy of Weston Solutions Inc.).
The soil medium, or substrate, is composed of 65% lightweight expandable shale, 15% biosolids or comparable compost, 10% Perlite or other lightweight additives, and 10% fines. The current composition may vary from the original due to dry deposition and natural seeding of additional plant life. Results from the vegetated roof media analysis performed by the Agricultural Analytical Services Laboratory at the Pennsylvania State University are provided in Tables 2-1 and 2-2.
Table 2-1: Vegetated roof media characteristics (Table Courtesy of Weston Solutions Inc.).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density Measurements</strong></td>
<td></td>
</tr>
<tr>
<td>Bulk Density (dry weight basis)</td>
<td>0.87 g/cm³</td>
</tr>
<tr>
<td>Bulk Density (at max. water-holding capacity)</td>
<td>1.18 g/cm³</td>
</tr>
<tr>
<td><strong>Water/Air Measurements</strong></td>
<td></td>
</tr>
<tr>
<td>Moisture (as received)</td>
<td>10.5 mass %</td>
</tr>
<tr>
<td>Total Pore Volume</td>
<td>60.7 Vol. %</td>
</tr>
<tr>
<td>Maximum water-holding Capacity</td>
<td>31.8 Vol. %</td>
</tr>
<tr>
<td>Air-Filled Porosity (at max water-holding capacity)</td>
<td>28.9 Vol. %</td>
</tr>
<tr>
<td>Water Permeability (Saturated Hydraulic Conductivity)</td>
<td>0.362 cm/s</td>
</tr>
<tr>
<td><strong>pH and Salt Content</strong></td>
<td></td>
</tr>
<tr>
<td>pH (CaCl₂)</td>
<td>6.5</td>
</tr>
<tr>
<td>Soluble salts (water, 1:10, m:v)</td>
<td>0.75 g(KCL)/L</td>
</tr>
<tr>
<td><strong>Organic Measurements</strong></td>
<td></td>
</tr>
<tr>
<td>Organic matter content</td>
<td>2.6 mass %</td>
</tr>
<tr>
<td><strong>Nutrients</strong></td>
<td></td>
</tr>
<tr>
<td>Phosphorous, P₂O₅ (CAL)</td>
<td>245.1 mg/L</td>
</tr>
<tr>
<td>Potassium, K₂O (CAL)</td>
<td>103.6 mg/L</td>
</tr>
<tr>
<td>Magnesium, Mg (CaCl₂)</td>
<td>101 mg/L</td>
</tr>
<tr>
<td>Nitrate + Ammonium (CaCl₂)</td>
<td>14.3 mg/L</td>
</tr>
</tbody>
</table>

Table 2-2: Vegetated roof particle size analysis (Table Courtesy of Weston Solutions Inc.).

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.002</td>
<td>1.4</td>
</tr>
<tr>
<td>0.002-0.05</td>
<td>3.2</td>
</tr>
<tr>
<td>0.05-0.25</td>
<td>2.6</td>
</tr>
<tr>
<td>0.25-1.0</td>
<td>3.3</td>
</tr>
<tr>
<td>1.0-2.0</td>
<td>4.3</td>
</tr>
<tr>
<td>2.0-3.2</td>
<td>7.0</td>
</tr>
<tr>
<td>3.2-6.3</td>
<td>37.2</td>
</tr>
<tr>
<td>6.3-9.5</td>
<td>34.2</td>
</tr>
<tr>
<td>9.5-12.5</td>
<td>6.8</td>
</tr>
<tr>
<td>&gt;12.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Modules are planted with a variety of species prior to installation which may have included *Allum schoenoprasum, Sedum kamtschaticum var. floriferum, Sedum caucicola, Sedum spurium, Sedum sieboldii, Sedum rubrotinctum, Sedum caucicola, Sedum rupestre, and Sedum pachyclados*. However, it is common to see certain species dominate over a period of time depending on what types of conditions the roof is subject to (shading,
winds, etc.). As these modules were fully mature, fewer numbers of species are present then originally planted. During the research period, four of the original species of sedums were present in the modules: including *Sedum rupestre*, *Sedum spurium*, *Sedum kamtschaticum*, and *Sedum rubrotinctum*.

2.1.5 Experimental Observations

Two identical experimental setups were used to gather data from the modules (Table 2-3). For each module, a datalogger collected and stored data (Figure 2-20), a load cell monitored the module weight (Figure 2-21), a tipping bucket measured precipitation (Figure 2-22), thermocouple wire monitored temperature data, and a thermister regulated these temperature readings (Figure 2-20). Four thermocouple wires were placed 25.4 cm above the module, on the surface of the module, and 2.5 and 7.6 cm below the soil medium surface (Figure 2-23 and Figure 2-24). The load cell, temperature, and precipitation readings were recorded every one, fifteen, and thirty minutes.

<table>
<thead>
<tr>
<th>Table 2-3: Data gathering equipment.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
</tr>
<tr>
<td>Hardware</td>
</tr>
<tr>
<td>Datalogger</td>
</tr>
<tr>
<td>Load Cell</td>
</tr>
<tr>
<td>Tipping Bucket</td>
</tr>
<tr>
<td>Thermocouple Cable</td>
</tr>
<tr>
<td>Thermister</td>
</tr>
<tr>
<td>Software</td>
</tr>
<tr>
<td>Datalogger Communication</td>
</tr>
</tbody>
</table>
Figure 2-20: Data logger and thermister (circled in red).

Figure 2-21: SSM Sealed S-Type 250 load cell.
Figure 2.22: Tipping bucket rain gauge.

Figure 2.23: Thermocouple wire on surface of module (circled in red).
Precipitation, temperature, and relative humidity (RH) data were gathered from an adjoining academic building Morse Hall with latitude 43.1347°N and longitude 70.9356°W (Figure 2-2). This UNH Weather Station is located atop the four story building. Data were obtained from www.weather.unh.edu. Solar radiation data were obtained from a weather station that is run by the National Oceanic and Atmospheric Administrations (NOAA) National Climactic Data Center (NCDC). The weather station is located on Kingman Farm with latitude 43.1721°N and longitude 70.9285°W (Figure 2-25) and is approximately 4 km from the research site. The tipping bucket and thermocouples measurements were used to provide independent checks of the Morse Hall data.
2.1.6 Module Calibration

Calibrations were performed on the load cell for Module #1 prior to placement at the site. In the laboratory, two calibrations were performed. The first took place over 4 days during which known weights were incrementally added for the first two days and removed for the last two days from the load cell. These weights varied from 50 to 64000 g. A second laboratory calibration was performed over a 4 hour period. This calibration added 750 g every thirty minutes to an hour and the 750 g were removed in the same manner. Finally, an hour-long, at site calibration was performed on the day of installation with the module and three known weights of 300, 750, and 4207.5 g. For each calibration, average load cell voltage measurements were plotted versus cumulative weight. The trendline fit to the data is

\[ dW = 37883 \cdot dV \]  

(2-1)
where $dW$ is the change in weight (g) and $dV$ is the change in voltage (mV). This relationship can be used to convert $dV$ to a corresponding $dW$. Using the density of water, weight changes may be converted to water volume changes. The load cell resolution is 0.001 mV which is equivalent to 37.883 g change in weight and 0.051 mm change in module water depth.

The second module was initially slightly heavier than the first. This may be due to differences in soil medium, or a higher initial moisture content. To account for this initial difference Module #2 soil water weight changes were adjusted to match that of Module #1. This enabled the researcher to determine if storage changes were consistent between modules.

In order to obtain a relationship between the load cell voltage and the module moisture content, laboratory tests were performed. Here it is assumed that Module #2 and Module #1 have the same soil moisture. This is a reasonable assumption because the modules were created from the same medium, are the same age, were subjected to the same environmental conditions for seven months and showed the same response over time.

Laboratory tests were conducted to determine soil moisture and soil properties in March 2010. Tests followed the steps outlined in the ASTM Standard Designation: D2974-07a (ASTM 2010). Immediately prior to the sampling, the load cell outputs were recorded. Following, approximately a 900 cm$^3$ soil sample (10 by 5 by 10 cm and 10 by 5 by 8 cm) with accompanying plant medium was removed from Module #2. The above ground plants were cut and placed in a separate pan from the soil media. The root masses were left intact within the soil media. The plant and soil samples were weighed
separately. The samples were then baked at a temperature of 105°C (the recommended temperature to avoid burning off the organics) for a period of 22 hours and reweighed. The samples were then replaced in the oven and baked for an additional two hours. No additional weight change occurred. Moisture contents of soil and plant samples are listed in Table 2-4. Test results indicated that the wet sample density was 0.84 g/cm³, the bulk density was 0.74 g/cm³, the soil water content was 92 g (0.10 cm³/ cm³), and the plant water content was 9.7 g.

<table>
<thead>
<tr>
<th>Media</th>
<th>Wt (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td></td>
</tr>
<tr>
<td>Soil Wet Weight</td>
<td>775.05</td>
</tr>
<tr>
<td>Soil Dry Weight</td>
<td>682.95</td>
</tr>
<tr>
<td>Soil Water Weight</td>
<td>92.10</td>
</tr>
<tr>
<td>Soil Volumetric Water Content</td>
<td>10%</td>
</tr>
<tr>
<td>Pant</td>
<td></td>
</tr>
<tr>
<td>Plant Wet Weight</td>
<td>14.50</td>
</tr>
<tr>
<td>Plant Dry Weight</td>
<td>4.80</td>
</tr>
<tr>
<td>Plant Water Weight</td>
<td>9.70</td>
</tr>
</tbody>
</table>

From the soil sample, a 10.0% moisture content corresponds to 2.304 mV load cell reading. Knowing the moisture content, volume, and area of the module, a water depth can be determined or calculated. Similarly, given the dry bulk density of soil, the module dry weight can be estimated. Additional details on the moisture content calibration equations are provided in Appendix A.

The final relationship between module weight and voltage is

\[ W = 37883V + 707.26 \]  \( (2-2) \)

where \( W \) is the weight (g) acting on the load cell and \( V \) is the load cell voltage (mV).

Water storage is calculated from (2-2)
\[
S = \frac{W - Dry_{\text{Weight}}}{743.22 \frac{g}{mm}}
\]  

(2-3)

where \( S \) is the depth of water (mm), \( Dry_{\text{Weight}} \) is the laboratory tested dry weight of the module (g), and 743.22 is a conversion for g to mm.

Soil moisture is relationship between the module storage and module depth

\[
\theta = \frac{S}{Module_{\text{Depth}}}
\]

(2-4)

where \( \theta \) is the soil moisture content of the module (mm/mm), and \( Module_{\text{Depth}} \) is equal to 101.6 mm.
Chapter 3 - Methodology (Model and Analysis)

3.1 Model

3.1.1 Model Introduction

A simple bucket model approach with a daily time step was used following Guswa (2002). The module is the control volume with inputs from precipitation and dew, and outputs that include drainage from the module, outflow out of the module and ET (Figure 3-1). Figure 3-2 shows the model’s process flow diagram. The model is forced using atmospheric data. Five calibration parameters are required for this vegetated roof model.
Figure 3-1: Model inputs and outputs where I is the precipitation that infiltrates into the module, D is dew formation, ET is the evapotranspiration, O is the outflow, and Dr is the drainage from the module.
3.1.2 Equations Used-Module Model

The vegetated roof model uses a water balance in depth units to characterize module water dynamics as

\[ \Delta S = P + D - Dr - ET - O \]  

(3-1)

where \( \Delta S \) is the change in storage over a time step \( \Delta t \) (mm), \( P \) is the precipitation (mm), \( D \) is the net nighttime input of water from the atmosphere (mm), \( Dr \) is the drainage through the module (mm), \( O \) is the outflow (mm), and \( ET \) is the evapotranspiration (mm) which includes both evaporation from the soil and water intercepted by the plants as well as plant transpiration.
The model, acting on a daily time step, sets storage at the beginning of a period to the final storage from the end of the previous day. The daily inputs and outputs are summed and applied to the final storage for that period.

\[ S_i = S_0 + P + D - Dr - ET - O \]  

(3-2)

where \( S_0 \) is the initial soil moisture (mm), \( P \) is the precipitation, \( D \) is the dew formation (mm), \( Dr \) is the drainage from the module (mm), \( ET \) is the evaportranspiration (mm), and \( O \) is the outflow (mm).

\( ET \) is estimated following the Guswa (2002) approach in which \( ET \) is estimated for a given potential \( ET_p \) and the soil water. In this study, \( ET_p \) is estimated using a reference \( ET \) (\( ET_o \)) and crop coefficient approach (Allen et al. 1998; Walter et al. 2000) where

\[ ET = \begin{cases} 
0 & \text{if } S \leq Sh \\
\frac{S - Sh}{S* - Sh} \times ET_p & \text{if } Sh < S < S* \\
ET_p & \text{if } S \geq S*
\end{cases} \]  

(3-3)

\[ ET_p = ET_o \times c \]  

(3-4)

\[ ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e)}{\Delta + \gamma (1 + C_n u_2)} \]  

(3-5)
where $Sh$ is the hygroscopic saturation (mm) or the soil water content at which $ET$ ceases, $S^*$ is the soil water content of stomatal closure (mm), $ET_p$ is the potential $ET$ (mm), and $c$ is the crop coefficient. On days with precipitation, $S$ (mm) is the net of initial storage, precipitation, drainage, and outflow. $ET_0$ is the standardized reference crop $ET$ (mm $day^{-1}$); $Rn$ is net radiation at the crop surface (MJ $m^{-2}$ $day^{-1}$); $G$ is soil heat flux at the soil surface (MJ $m^{-2}$ $day^{-1}$); $T$ is mean daily or hourly air temperature at 1.5–2.5-m height (°C); $u_2$ is mean daily or hourly wind speed at 2-m height (m $s^{-1}$); $e_s$ is mean saturation vapor-pressure at 1.5–2.5-m height (kPa) (for daily computation, the value is the average of $e_s$ at maximum and minimum air temperature); $e$ is mean actual vapor-pressure at 1.5–2.5-m height (kPa); $\Delta$ is slope of the saturation vapor-pressure-temperature curve (kPa °C$^{-1}$); $g$ is psychrometric constant (kPa °C$^{-1}$); $C_n$ is numerator constant for reference type and calculation time step; and $C_d$ is denominator constant for reference type and calculation time step. For daily time steps, the constants $C_n$ and $C_d$ are 900 and 0.34, respectively. The values of $Rn$ and $G$ in (3-5) are estimated from measured values of incoming solar radiation as described by Walter et al. (2000).

To determine drainage, precipitation that can be infiltrated into the soil medium, $I$ (mm), is calculated based on the rainfall and available module storage as

$$I = \min(P, S_{Max} - S_o)$$  \hspace{1cm} (3-6)
where $P$ is precipitation (mm), $S_{\text{Max}}$ is the maximum water storage capable within the module (mm), and $S_o$ is the initial soil moisture (mm).

Based on the infiltrated volume, the module drainage, $Dr$, drains to field capacity on a daily basis

$$Dr = \begin{cases} 
0 & \text{if } I + S_o \leq S_{fc} \\
I + S_o - S_{fc} & \text{if } I + S_o > S_{fc}
\end{cases}$$

where $S_{fc}$ is the saturated field capacity, the point at which the suction force within the soil is equal to the gravitational force, for the module.

Any precipitation that falls within a time period that exceeds the soils water holding capacity becomes outflow, $O$, and is immediately drained. Outflow does not refer to water spilling over the sides of a module, but rather runoff that is drained immediately through the perforations below. Drainage also exits these perforations, but at varying rates. Outflow is modeled as exiting instantaneously through these perforations.

$$O = \begin{cases} 
0 & \text{if } P < I \\
P - I & \text{if } P > I
\end{cases}$$

Dew, $D$, is calculated by multiplying a physical parameter by a dew coefficient. The ability of known physical parameters to predict the magnitude of dew measures was
relatively poor. Solar radiation had the best linear relationship ($R^2 = 0.258$) with a trend line equation

$$D = 0.0085S_R + 0.0046$$ (3-9)

where $D$ is the daily dew (mm $day^{-1}$) and $S_R$ is the daily solar radiation (MJ/m$^2$/d). A relationship between dew formation and $S_R$ was determined for the research period and applied to the model.

In summary, the model requires five parameters. The three vegetation parameters are; $Sh$, $S^*$, and $c$. The soil characteristics are $S_{max}$ and $S_{fc}$. The parameters will be determined using the data from the first four weeks of the experiment.

### 3.1.3 Model Application at a Municipal Scale

The model will be applied at a municipal scale by considering available rooftops within downtown Portsmouth, NH. The approach is to identify all roof area as well as those roofs in which vegetated roofs can be used. This rooftop space represents the potential vegetated roof space within the study site. Because structural capacity and zoning issues are not well defined, only slope will be used to determine potential rooftop space. The model will be run for an 8-year period (2002-2009). The required historic atmospheric data will be collected from the Morse Hall and Kingman Farm weather stations for the time period 1/1/2002 – 12/31/2009.
3.3 Statistical Tests

Model performance statistics include difference and summary univariate, a statistic that utilizes a single dependent variable as well as indices to evaluate the ability of the model predictions to replicate observations. The observed drainage, ET, and storage values will be compared to predicted values and are compared using both the Nash Sutcliffe equation (J. E. Nash 1970) and metrics described in Willmott (1982).

\[
E = 1 - \left( \frac{\sum_{i=1}^{N} (D_{\text{obs},i} - D_{\text{pre},i})^2}{\sum_{i=1}^{N} (D_{\text{obs},i} - \bar{D}_{\text{obs},i})^2} \right) \tag{3-10}
\]

where \( N \) is the number of comparisons being made in each analysis, \( D_{\text{obs},i} \) is the observed, depth of water (mm), \( D_{\text{pre},i} \) is the predicted depth (mm), and \( \bar{D}_{\text{obs},i} \) is the average of the observed depths (mm).

\( MAE \), the mean absolute error of the compared data sets, is given as

\[
MAE = N^{-1} \sum_{i=1}^{N} |P_i - O_i| \tag{3-11}
\]

where \( O_i \) and \( P_i \) are the observed and predicted values, respectively.

The root mean square error (\( RMSE \)) is the average differences between observed and predicted values, given as
\[ RMSE = \left( \frac{1}{N-1} \sum_{i=1}^{N} (P_i - O_i)^2 \right)^{0.5} \] (3-12)

\( RMSE_s \) and \( RMSE_u \) are the root mean square errors for both systematic error \( (MSE_s) \) and unsystematic error \( (MSE_u) \), given as

\[ RMSE_s = \sqrt{N^{-1} \sum_{i=1}^{N} (\hat{P}_i - O_i)^2} \] (3-13)

\[ RMSE_u = \sqrt{N^{-1} \sum_{i=1}^{N} (P_i - \hat{P}_i)^2} \] (3-14)

where \( \hat{P}_i \) is the predicted value from the least-squares regression and is equal to \( a + b * O_i \).

The index of agreement \( (d) \) is a descriptive measure that is both a relative and bounded measure which enables cross comparisons between models (Willmott 1982). \( d \) is calculated as

\[ d = 1 - \left[ \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (|P_i| - |O_i|)^2} \right] , 0 \leq d \leq 1 \] (3-15)
where \( P'_i = P_i - \bar{O} \) and \( O'_i = O_i - \bar{O} \). \( \bar{O} \) and \( \bar{P} \) are the average of the observed data and the predicted data, respectively.
Chapter 4 – Results

4.1 Experimental Results

Module #1 (M#1) was monitored from Julian day 215 to 334 (August 3rd to November 30th) in 2009. Due to artificial watering and shading, the research period started on Julian day 219. Module #2 (M#2) was deployed from Julian day 259 to 334. The module weight and temperature as well as precipitation were monitored continuously over the research period. The data are complete except for a power outage at the University that halted readings on Julian day 264 from 1400 to 1430.

Precipitation (greater than or equal to 0.254 mm) was recorded on 35 of the 116 days. Daily precipitation ranged from events equal to one tip of the tipping bucket, 0.254 mm (0.01 in), to 55.12 mm. Air temperatures ranged from -4.3 to 32.5°C, relative humidity was between 22.2 and 100%, wind speeds were between 1.57 and 6.58 m/s, and incoming solar radiation was between 0 and 28.6 MJ/m²/day. The Durham, NH historical climate data were obtained for the period of record, 1940 to 2008, from NOAA NCDC (Table 4-1). The August through November, 2009 study period had an identical average temperature and slightly less precipitation.
Table 4-1: The 2009 four month (August to November) temperature and precipitation values for the study period and the historical period (1940 to 2008). Historical period obtained from NCDC station #272174.

<table>
<thead>
<tr>
<th>Averaging Period</th>
<th>Tmin (°C)</th>
<th>Tmax (°C)</th>
<th>Tmean (°C)</th>
<th>Precip (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study Period</td>
<td>7.9</td>
<td>17.8</td>
<td>12.8</td>
<td>317.1</td>
</tr>
<tr>
<td>Historical Period</td>
<td>6.0</td>
<td>19.4</td>
<td>12.8</td>
<td>391.4</td>
</tr>
</tbody>
</table>

Figures 4-1 through 4-4 show the vegetated roof storage and soil moisture measurements for M#1 and M#2 on a 30 minute time step. After its installation in mid-September, M#2 parallels the water storage in M#1, helping to support the results. Water storage in M#1 ranged from 0.90 to 17.00 mm with average monthly storage values from August to November of 5.2, 4.2, 10.8, and 11 mm, respectively.

Periods that have a rapid increase in storage correspond to precipitation events. A sharp decrease immediately following an increase represents a period in which the modules are draining. Decreases during days with no precipitation are attributed to ET. These figures show small increases in water (up to 0.11 mm) during the night. This increase was attributed to the formation of dew and is included in the water balance. August and September exhibit few precipitation events followed by extended drying periods (Figures 4-1 and 4-2). October and November contain more frequent events and less daily drying occurs than in previous months (Figures 4-3 and 4-4). This decrease in time between events and lower ET rates prevents the module storage from dropping below 7 mm. This limits the modules’ capability to retain precipitation.
Figure 4-1: M#1 depth of water in storage and soil moisture content August 7th-31st, 2009.
Figure 4-2: M#1 and M#2 depth of water in storage and soil moisture content September 1st-30th, 2009.

Figure 4-3: M#1 and M#2 depth of water in storage and soil moisture content October 1st-31st, 2009.
Figure 4-4: M#1 and M#2 depth of water in storage and soil moisture content November 1st-30th, 2009.

The time series of precipitation events and runoff show that for the largest rainfall events drainage nearly equals precipitation (Figure 4-5). Small precipitation events have little or no drainage. However, small storms that immediately follow large storms have drainage nearly equal to storage due to wet initial soil conditions.
For the 30 precipitation events, stormwater retention ranged from 0 to 100% with an average of 57% retained per storm (Figure 4-6). As storm depth increases percent retained declines. Events exceeding 10 mm rarely have more than a 75% reduction. The one exception in this study is a 11.2 mm event on a module with initial storage moisture of 0.02 m$^3$/m$^3$ (Table 4-2). The relatively dry antecedent conditions resulted in a high
percentage retention (88%). This example demonstrates importance of initial soil moisture in stormwater retention. Percent retention for the heavy events depends on initial soil moisture and event duration and depth and varies between 0 and 50% retention.

Figure 4-6: Total precipitation versus the drainage for 30 event days from August 7th to November 30th, 2009.

Over the research period, 17 light events (<10 mm), 11 medium events (≥10 and <25 mm), and 2 heavy events (≥25 mm) occurred. The average percentages retained for light, medium, and heavy events were 73, 39, and 16%, respectively. Seven out of the 17 light events achieved 100% retention. Additional weather conditions are provided in Table 4-2. Not all light events had high retention, notably one light event (0.36 mm) had 0% retention when the initial soil moisture was 0.12 m³/m³. Larger events had lower
percent retention, but greater magnitudes of stormwater retention. For the 11 medium
events, a consistent relationship between initial soil moisture and module retention is
evident. Other factors such as storm duration also play an important role in module
retention. Longer duration storms allow the module to lower the soil moisture content
through ET even during the event. Regardless of the initial soil moisture, the percent
retained will be low for a heavy event because water holding capacity is limited.
<table>
<thead>
<tr>
<th>Month</th>
<th>Julian Day</th>
<th>Duration (day)</th>
<th>Air Temp (°C)</th>
<th>RH (%)</th>
<th>Wind Speed (km/h)</th>
<th>PAR (µE)</th>
<th>Solar Radiation (MJ/m²/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>219 - 243</td>
<td>25</td>
<td>Average</td>
<td>21.2</td>
<td>82.7</td>
<td>8.3</td>
<td>483.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>32.5</td>
<td>102.9</td>
<td>21.4</td>
<td>2100.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>10.8</td>
<td>32.7</td>
<td>2.5</td>
<td>0.0</td>
</tr>
<tr>
<td>September</td>
<td>244 - 273</td>
<td>30</td>
<td>Average</td>
<td>15.4</td>
<td>80.8</td>
<td>8.9</td>
<td>417.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>26.8</td>
<td>103.5</td>
<td>22.9</td>
<td>1860.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>2.8</td>
<td>33.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>October</td>
<td>274 - 304</td>
<td>31</td>
<td>Average</td>
<td>8.6</td>
<td>81.8</td>
<td>9.6</td>
<td>208.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>19.7</td>
<td>103.9</td>
<td>26.7</td>
<td>1413.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>-1.5</td>
<td>27.9</td>
<td>3.8</td>
<td>0.0</td>
</tr>
<tr>
<td>November</td>
<td>305 - 334</td>
<td>30</td>
<td>Average</td>
<td>7.2</td>
<td>78.7</td>
<td>9.8</td>
<td>148.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>26.0</td>
<td>103.6</td>
<td>36.2</td>
<td>1111.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>-4.3</td>
<td>22.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Event Time</td>
<td>Date and Time</td>
<td>Precipitation (mm)</td>
<td>Drainage (mm)</td>
<td>Time to Peak (hr)</td>
<td>Time to Peak (hr) D</td>
<td>Peak Intens (mm/30 min)</td>
<td>Peak Intens (mm/30 min) D</td>
</tr>
<tr>
<td>-------------</td>
<td>---------------------</td>
<td>--------------------</td>
<td>---------------</td>
<td>-------------------</td>
<td>---------------------</td>
<td>-------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Light</td>
<td>242.90 August 30th, 21:29</td>
<td>0.25</td>
<td>0.00</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>261.75 September 18th, 16:00</td>
<td>0.25</td>
<td>0.05</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>304.56 October 31st, 13:30</td>
<td>0.36</td>
<td>0.36</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>282.73 October 9th, 17:30</td>
<td>0.51</td>
<td>0.00</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>328.08 November 24th, 2:00</td>
<td>0.51</td>
<td>0.30</td>
<td>0.5</td>
<td>2.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>254.81 September 11th, 19:30</td>
<td>0.76</td>
<td>0.00</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>295.08 October 22nd, 2:00</td>
<td>0.76</td>
<td>0.00</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>255.94 September 12th, 22:30</td>
<td>1.27</td>
<td>0.76</td>
<td>3.5</td>
<td>4.5</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>309.52 November 5th, 12:30</td>
<td>1.27</td>
<td>0.36</td>
<td>0.5</td>
<td>3.0</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>283.08 October 10th, 2:00</td>
<td>1.52</td>
<td>0.05</td>
<td>2.0</td>
<td>0.5</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>334.40 November 30th, 9:30</td>
<td>2.03</td>
<td>0.00</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>323.33 November 25th, 0:00</td>
<td>2.09</td>
<td>0.97</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>304.92 October 31st, 22:00</td>
<td>2.29</td>
<td>0.00</td>
<td>0.5</td>
<td>0.5</td>
<td>1.8</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>286.23 October 13th, 5:30</td>
<td>4.83</td>
<td>1.21</td>
<td>4.5</td>
<td>5.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>223.73 August 11th, 17:30</td>
<td>5.08</td>
<td>1.97</td>
<td>1.5</td>
<td>3.8</td>
<td>0.8</td>
<td>7.75</td>
</tr>
<tr>
<td></td>
<td>233.83 August 21st, 20:00</td>
<td>5.33</td>
<td>0.00</td>
<td>0.5</td>
<td>0.5</td>
<td>4.6</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>324.27 November 20th, 6:30</td>
<td>9.91</td>
<td>7.36</td>
<td>3.5</td>
<td>3.5</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Medium</td>
<td>291.55 October 18th, 13:30</td>
<td>10.67</td>
<td>6.03</td>
<td>4.0</td>
<td>5.5</td>
<td>1.3</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>270.23 September 27th, 16:00</td>
<td>11.18</td>
<td>1.34</td>
<td>2.0</td>
<td>15.0</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>223.33 August 11th, 8:00</td>
<td>12.45</td>
<td>5.56</td>
<td>1.0</td>
<td>7.6</td>
<td>5.1</td>
<td>2.91</td>
</tr>
<tr>
<td></td>
<td>271.90 September 28th, 21:30</td>
<td>12.95</td>
<td>8.93</td>
<td>0.5</td>
<td>4.3</td>
<td>2.8</td>
<td>10.35</td>
</tr>
<tr>
<td></td>
<td>301.35 October 28th, 8:30</td>
<td>14.99</td>
<td>11.67</td>
<td>6.0</td>
<td>7.5</td>
<td>2.0</td>
<td>11.47</td>
</tr>
<tr>
<td></td>
<td>234.56 August 22nd, 13:30</td>
<td>15.24</td>
<td>9.68</td>
<td>0.5</td>
<td>13.0</td>
<td>7.5</td>
<td>11.27</td>
</tr>
<tr>
<td></td>
<td>276.19 October 3rd, 4:30</td>
<td>17.02</td>
<td>12.07</td>
<td>14.5</td>
<td>14.5</td>
<td>3.8</td>
<td>8.46</td>
</tr>
<tr>
<td></td>
<td>255.44 September 12th, 10:30</td>
<td>17.53</td>
<td>8.81</td>
<td>4.5</td>
<td>5.0</td>
<td>3.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>280.15 October 7th, 3:30</td>
<td>18.54</td>
<td>10.25</td>
<td>4.0</td>
<td>4.0</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>295.96 October 23rd, 23:00</td>
<td>21.84</td>
<td>17.66</td>
<td>16.0</td>
<td>16.0</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>331.31 November 27th, 7:30</td>
<td>22.86</td>
<td>20.57</td>
<td>8.0</td>
<td>8.5</td>
<td>2.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Heavy</td>
<td>240.95 August 28th, 23:00</td>
<td>45.21</td>
<td>36.04</td>
<td>6.0</td>
<td>6.0</td>
<td>4.3</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>319.27 November 14th, 6:30</td>
<td>56.64</td>
<td>50.17</td>
<td>10.0</td>
<td>10.0</td>
<td>4.1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Note: CN denoted with a "<" are the upperbound CN values for the particular event.
These daily precipitation values from 1940 to 2008 were rank-ordered from smallest to largest and assigned a Weibull exceedence probability. With respect to the median retention capability (3.32 mm from Table 4-3) during a precipitation events for this study, Figure 4-7 shows that the module would have contained approximately 60% of the storms over the 68 year period in Durham, NH.

Figure 4-7: Precipitation events over the 68 year historic period for Durham, NH versus the exceedence probability of each size storm. 3.32 mm is the median retention capability of the module for the 2009 four month research period.
Curve Numbers (CN), while designed for small watershed applications, are commonly used to estimate run-off for engineering scale analyses. For each storm captured by M#1 a CN was calculated. These values are shown between the 90 to 100 CN curves Figure 4-8. Figure 4-9 shows the antecedent soil moisture and the corresponding CN for each storm event to illustrate the importance of antecedent conditions on runoff.

![Figure 4-8: SCS curve numbers (CN) shown for rain event captured by M#1.](image)

Figure 4-8: SCS curve numbers (CN) shown for rain event captured by M#1.
Figure 4-9: Antecedent soil moisture conditions and CN shown for each event captured by M#1.

Figure 4-10: ET values by day from August 7th-November 30th, 2009.
The weekly and monthly water balances are summarized in Table 4-4. August through November had 52.6, 19.8, 62.5, and 78.8 mm of drainage, respectively, with a maximum daily drainage of 48.3 mm. The monthly module retention ranged from 17 to 55% of the monthly precipitation. In the latter periods, modest water losses were noted at night. It is likely that some additional ET losses occur at night. Because it was not possible to separate nighttime ET (NET) from dew, the net water loss or gain at night is reported. Total ET was 31.0, 27.3, 23.1, and 15.7 mm for August through November, respectively, with a maximum daily ET of 2.75 mm. ET values decreased over the research period. As shown in Figure 4-10, ET varies from 0.20 to 2.75 mm during August and September between 0.00 and 2.29 mm/day during October and November. The ET value of 2.29 mm occurs in early October. A consistent decrease in daily ET is evident for the remainder of October and November with a few values exceeding 1.5 mm day$^{-1}$. Not until late November is a comparable value, 1.78 mm day$^{-1}$, obtained.
<table>
<thead>
<tr>
<th>Julian Day</th>
<th>Days</th>
<th>Precip. (mm)</th>
<th>ET (mm)</th>
<th>Drainage (mm)</th>
<th>Dew/NET (mm)</th>
<th>Avg. Storage (mm)</th>
<th>Stormwater Retention</th>
<th>Volumetric Reduction (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 219 - 243</td>
<td>25</td>
<td>83.6</td>
<td>31.0</td>
<td>52.6</td>
<td>3.5</td>
<td>6.0</td>
<td>37%</td>
<td>0.023</td>
</tr>
<tr>
<td>Week 1: 219-224</td>
<td>6</td>
<td>17.5</td>
<td>6.9</td>
<td>7.5</td>
<td>0.9</td>
<td>5.4</td>
<td>57%</td>
<td>0.005</td>
</tr>
<tr>
<td>Week 2: 225-230</td>
<td>6</td>
<td>0.0</td>
<td>8.3</td>
<td>0.0</td>
<td>1.2</td>
<td>5.4</td>
<td>NA</td>
<td>0.006</td>
</tr>
<tr>
<td>Week 3: 231-236</td>
<td>6</td>
<td>20.6</td>
<td>6.3</td>
<td>9.1</td>
<td>0.3</td>
<td>5.4</td>
<td>56%</td>
<td>0.005</td>
</tr>
<tr>
<td>Week 4: 237-243</td>
<td>7</td>
<td>45.5</td>
<td>9.5</td>
<td>36.0</td>
<td>1.2</td>
<td>7.5</td>
<td>21%</td>
<td>0.007</td>
</tr>
<tr>
<td>September 244 - 273</td>
<td>30</td>
<td>43.9</td>
<td>27.3</td>
<td>19.8</td>
<td>4.1</td>
<td>4.9</td>
<td>55%</td>
<td>0.020</td>
</tr>
<tr>
<td>Week 1: 244-251</td>
<td>8</td>
<td>0.0</td>
<td>9.0</td>
<td>0.0</td>
<td>2.1</td>
<td>4.3</td>
<td>NA</td>
<td>0.007</td>
</tr>
<tr>
<td>Week 2: 252-259</td>
<td>8</td>
<td>19.6</td>
<td>7.2</td>
<td>9.5</td>
<td>1.3</td>
<td>5.3</td>
<td>51%</td>
<td>0.005</td>
</tr>
<tr>
<td>Week 3: 260-266</td>
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<td>0.3</td>
<td>5.0</td>
<td>0.1</td>
<td>1.2</td>
<td>3.9</td>
<td>80%</td>
<td>0.004</td>
</tr>
<tr>
<td>Week 4: 267-273</td>
<td>7</td>
<td>24.1</td>
<td>6.1</td>
<td>10.3</td>
<td>-0.5</td>
<td>6.2</td>
<td>57%</td>
<td>0.005</td>
</tr>
<tr>
<td>October 274 - 304</td>
<td>31</td>
<td>90.7</td>
<td>23.1</td>
<td>62.5</td>
<td>-2.9</td>
<td>11.6</td>
<td>31%</td>
<td>0.017</td>
</tr>
<tr>
<td>Week 1: 274-280</td>
<td>7</td>
<td>35.6</td>
<td>6.6</td>
<td>26.2</td>
<td>0.2</td>
<td>11.0</td>
<td>26%</td>
<td>0.005</td>
</tr>
<tr>
<td>Week 2: 281-288</td>
<td>8</td>
<td>6.9</td>
<td>7.2</td>
<td>1.1</td>
<td>0.1</td>
<td>11.4</td>
<td>84%</td>
<td>0.005</td>
</tr>
<tr>
<td>Week 3: 289-296</td>
<td>8</td>
<td>11.7</td>
<td>4.9</td>
<td>5.9</td>
<td>-0.9</td>
<td>11.3</td>
<td>50%</td>
<td>0.004</td>
</tr>
<tr>
<td>Week 4: 297-304</td>
<td>8</td>
<td>39.1</td>
<td>4.8</td>
<td>29.1</td>
<td>-2.2</td>
<td>12.8</td>
<td>26%</td>
<td>0.004</td>
</tr>
<tr>
<td>November 305 - 334</td>
<td>30</td>
<td>95.3</td>
<td>15.7</td>
<td>78.8</td>
<td>-1.0</td>
<td>11.8</td>
<td>17%</td>
<td>0.012</td>
</tr>
<tr>
<td>Week 1: 305-311</td>
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<td>1.3</td>
<td>4.2</td>
<td>0.0</td>
<td>-0.4</td>
<td>11.7</td>
<td>NA</td>
<td>0.003</td>
</tr>
<tr>
<td>Week 2: 312-318</td>
<td>7</td>
<td>55.1</td>
<td>2.7</td>
<td>48.3</td>
<td>-0.1</td>
<td>9.8</td>
<td>12%</td>
<td>0.002</td>
</tr>
<tr>
<td>Week 3: 319-326</td>
<td>8</td>
<td>11.4</td>
<td>4.8</td>
<td>9.2</td>
<td>-0.4</td>
<td>12.6</td>
<td>20%</td>
<td>0.004</td>
</tr>
<tr>
<td>Week 4: 327-334</td>
<td>8</td>
<td>27.5</td>
<td>4.0</td>
<td>21.7</td>
<td>-0.2</td>
<td>12.8</td>
<td>21%</td>
<td>0.003</td>
</tr>
</tbody>
</table>

**Daily Maximum**
- 55.1 2.3 48.3 0.6 17.0

**Daily Minimum**
- 0.0 0.0 0.0 -0.9 0.9

**Average**
- 2.7 0.8 1.8 0.03 8.7 32%

**Total**
- 116 313.5 97.1 213.7 3.7 0.077
4.2 Model Results

4.2.1 Parameter Estimation

The model requires five parameters. The three vegetation parameters are Sh, S*, and c. The soil characteristics are SMax and Sfc. The parameters were determined using the data from the first four weeks of the experiment. Utilizing the model equations from section 3.1.2, the parameters were optimized to minimize the mean absolute error (MAE) between observed and predicted ET and drainage values. First the vegetation parameters were optimized to minimize ET MAE while all other parameters remained constant. The resulting parameters, Sh = 0.0011 m³/m³, S* = 0.1114 m³/m³, c = 0.53 gave an MAE of 0.186 mm and remain constant over the research period. Once established, the vegetation parameters were fixed and the soil parameters were optimized to minimize drainage MAE. Because a change in storage occurred in early October, the Sfc soil parameter was optimized for the four week periods beginning on August 7th and again on October 1st. The resulting best fit parameters were SMax = 29.6 mm for the entire research period while Sfc = 0.1264 m³/m³ for August and September and 0.1399 m³/m³ for October and November. The change in Sfc that happens at this time (between September and October) is most likely due to the cooler and wetter period of October to November.

Once the model parameters were obtained, they were reviewed graphically. Figure 4-11 shows the measured module soil moisture versus the measured ET/ETo for days with no precipitation and the form of models ET function below (eqn. (3-3). August
and September consistently had a soil moisture drier than S*. October and November conditions rarely were below S* and had relatively high and variable ET/ET₀ due to the well watered conditions.

Figure 4-11: Relative ET as compared to soil moisture. The black line shows model function of soil moisture versus ET/ET₀ with respect to stressed or non-stressed conditions. S* and Sh represent the wilting point and the hygroscopic saturation (point at which evaporation ceases), respectively.

4.2.2 Model Performance

The module model was used to predict the module water balance from Julian day 215 to 334 (August 7th to November 30th) in 2009. Figure 4-12 shows the observed and predicted soil water storage evolution over the research period. For the first two months (up to Julian day 274), the model predicts the peaks from precipitation events and the initial drying period well. Over a prolonged drying period, the model appears to under estimate ET. In the later months, the frequent precipitation events prevent long term drying and keep the soil water storage above 8 mm. Between Julian days 312 to 318 the
model drastically over predicts ET. This occurs during the first freezing conditions of the year. This may have reduced the plants' actual ET and led to an overestimation of ET.

Figure 4-12: Observed and predicted daily values from August 7th to November 30th, 2009.
Figure 4-13 compares predicted drainage values to observed values. Events that occur over multiple days are included for the day that the event began. The model accurately predicts drainage for both the light and heavy events. As mentioned previously, events over 10 mm achieve stormwater retention less than 75% with the exception of one event. This event with dry antecedent conditions resulted in a high percent retention and as shown below the model captured this result.

Figure 4-13: Measured and modeled drainage by rainfall event versus precipitation.
The model performance statistics are summarized for drainage, storage, and ET in Table 4-5. The model does an excellent job predicting drainage ($R^2 = 0.98$) and storage ($R^2 = 0.94$). It does not perform as well when predicting ET ($R^2 = 0.59$). The Nash Sutcliffe efficiency coefficient, $E$, supports this finding with drainage, storage, and ET $E$ values of 0.98, 0.93, and 0.57, respectively. The observed and predicted mean values ($\bar{O}$ and $\bar{P}$) agree well for all three terms. Willmott (1982) states that the systematic differences, $RMSE_s$, in the model should approach 0 while the unsystematic differences, $RMSE_u$, should approach the $RMSE$ (Table 4-5). $RMSE$, are due to aspects such as poor instrument calibration and faulty methods of observation. Most of the error in this analysis is unsystematic for drainage, storage, and ET.
Table 4-5: Drainage, storage and ET model performance summary statistics. August 7th to November 30th, 2009.

<table>
<thead>
<tr>
<th></th>
<th>Obar</th>
<th>Pbar</th>
<th>so</th>
<th>sp</th>
<th>N</th>
<th>a</th>
<th>b</th>
<th>d</th>
<th>MAE</th>
<th>RMSE</th>
<th>RMSEs</th>
<th>RMSEu</th>
<th>r²</th>
<th>Nash-Sutcliffe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage</td>
<td>6.10</td>
<td>6.15</td>
<td>9.89</td>
<td>9.64</td>
<td>35</td>
<td>0.26</td>
<td>0.97</td>
<td>1.00</td>
<td>0.90</td>
<td>1.31</td>
<td>0.34</td>
<td>1.27</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Storage</td>
<td>8.89</td>
<td>9.21</td>
<td>4.01</td>
<td>3.83</td>
<td>117</td>
<td>0.99</td>
<td>0.92</td>
<td>0.98</td>
<td>0.83</td>
<td>1.04</td>
<td>0.43</td>
<td>0.95</td>
<td>0.94</td>
<td>0.93</td>
</tr>
<tr>
<td>ET</td>
<td>0.93</td>
<td>0.91</td>
<td>0.55</td>
<td>0.48</td>
<td>116</td>
<td>0.29</td>
<td>0.67</td>
<td>0.87</td>
<td>0.25</td>
<td>0.36</td>
<td>0.18</td>
<td>0.31</td>
<td>0.59</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Note: N, b, d, R² are dimensionless. The remaining terms have the units mm/day.
Scatter plots of the measured and modeled values are shown in Figures 4-14 to 4-16. Model results for drainage nearly always follow the 1:1 line. Storage results follow the 1:1 line for all values except a cluster of values from 8 to 10 mm. These values, however, were recorded from November 9th to November 14th, 2009 and during freezing conditions. ET values are somewhat skewed and have greater variability around the 1:1 line. However as shown in Table 4-5, the average observed and predicted values for ET are nearly identical. In addition, the standard deviations are low. While ET has a relatively low R² value, it is relatively unbiased and does not appear to impact storage and drainage predictions Overall the model, which was created to predict drainage, provides a highly accurate estimation of vegetated roof drainage and storage.
Figure 4-14: Scatter plot of daily observed versus predicted drainage. 1:1 line shown in blue.

Figure 4-15: Scatter plot of daily observed versus predicted storage. 1:1 line shown in blue.
4.2.3 Municipal Application Model Results

The model was run over an eight year historic period (1/1/2002 to 12/31/2009) for Seacoast New Hampshire weather patterns. The model used the calibration parameters determined in the previous section with the $S_{fc}$ set to 0.1399 m$^3$/m$^3$. These are results generally applicable to the Seacoast region and any other area with similar precipitation events and atmospheric conditions. Precipitation (greater than or equal to 0.254 mm) was recorded on 38% (1135 of the 3018 days). Daily precipitation ranged from events equal to one tip of the tipping bucket, 0.254 mm (0.01 in), to 135 mm (5.3 in). Air temperatures ranged from -27.6 to 36.4°C, relative humidity was between 11.6 and
100%, wind speeds were between 1.24 and 7.8 m/s, and incoming solar radiation was between 0 and 31.6 MJ/m²/day.

Monthly summations of precipitation, drainage, and percent stormwater retained are listed in Table 4-6. Monthly averages, maximums, and minimums are a good indicator of module stormwater retention for that time frame. July and August have relatively low rainfall with lowest precipitation values of 21.8 and 35.6 mm in 2005 and 2007, respectively, as well as the driest soil.

Over the historic model period, 797 light events (<10 mm), 232 medium events (≥10 and <25 mm), and 106 heavy events (≥25 mm) occurred. The average percentages retained for light, medium, and heavy events were 70, 25, and 10%, respectively. Figure 4-17 shows total precipitation for the months April to October over the historic model period. Winter months were been excluded because module performance for freezing temperatures has not been verified. The highest percent retention occurs in August, the month with the least precipitation. When allowed to have sufficient drying after precipitation, modules will retain a higher percent of the stormwater for the following event.
Figure 4-17: Total precipitation and amount retained for each month from 1/1/2002 to 12/31/2009 with respective percent stormwater retained.
Table 4-6: Modeled monthly average, maximums, and minimum water balance terms for the 8 year historic period (1/1/2002 - 12/31/2009) in Portsmouth, NH. Note winter vegetated roof performance (italicized months) has not been verified.

<table>
<thead>
<tr>
<th>Month</th>
<th>Avg.</th>
<th>Max</th>
<th>Min</th>
<th>Avg</th>
<th>Max</th>
<th>Min</th>
<th>Avg</th>
<th>Max</th>
<th>Min</th>
<th>Avg</th>
<th>Max</th>
<th>Min</th>
<th>Avg</th>
<th>Max</th>
<th>Min</th>
<th>Avg</th>
<th>Max</th>
<th>Stormwater Retained</th>
<th>Stormwater Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.12</td>
<td>0.13</td>
<td>0.11</td>
<td>12.3</td>
<td>13.5</td>
<td>10.9</td>
<td>65.2</td>
<td>95.5</td>
<td>13.7</td>
<td>53.7</td>
<td>82.2</td>
<td>4.6</td>
<td>12.4</td>
<td>14.8</td>
<td>10.3</td>
<td>0.0</td>
<td>0.0</td>
<td>23</td>
<td>66</td>
</tr>
<tr>
<td>February</td>
<td>0.11</td>
<td>0.13</td>
<td>0.09</td>
<td>11.6</td>
<td>13.4</td>
<td>8.9</td>
<td>78.5</td>
<td>210.6</td>
<td>27.4</td>
<td>62.3</td>
<td>197.5</td>
<td>14.9</td>
<td>16.6</td>
<td>20.0</td>
<td>12.8</td>
<td>0.0</td>
<td>0.0</td>
<td>28</td>
<td>46</td>
</tr>
<tr>
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<td>0.10</td>
<td>0.12</td>
<td>0.08</td>
<td>10.2</td>
<td>12.2</td>
<td>7.6</td>
<td>93.2</td>
<td>167.1</td>
<td>26.7</td>
<td>68.3</td>
<td>141.2</td>
<td>16.3</td>
<td>24.9</td>
<td>31.9</td>
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<td>0.0</td>
<td>0.0</td>
<td>30</td>
<td>48</td>
</tr>
<tr>
<td>April</td>
<td>0.09</td>
<td>0.10</td>
<td>0.07</td>
<td>8.9</td>
<td>10.1</td>
<td>6.9</td>
<td>135.8</td>
<td>291.6</td>
<td>86.1</td>
<td>105.3</td>
<td>256.9</td>
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<td>32.4</td>
<td>37.5</td>
<td>27.7</td>
<td>0.0</td>
<td>0.0</td>
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<td>37</td>
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<tr>
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<td>0.08</td>
<td>0.10</td>
<td>0.05</td>
<td>8.3</td>
<td>10.6</td>
<td>5.0</td>
<td>151.8</td>
<td>404.4</td>
<td>25.4</td>
<td>118.4</td>
<td>374.7</td>
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<td>37.4</td>
<td>45.4</td>
<td>26.7</td>
<td>3.9</td>
<td>4.9</td>
<td>30</td>
<td>52</td>
</tr>
<tr>
<td>June</td>
<td>0.08</td>
<td>0.10</td>
<td>0.05</td>
<td>8.4</td>
<td>10.5</td>
<td>4.7</td>
<td>111.8</td>
<td>228.3</td>
<td>45.2</td>
<td>75.5</td>
<td>183.2</td>
<td>8.2</td>
<td>42.5</td>
<td>55.4</td>
<td>23.5</td>
<td>4.2</td>
<td>4.8</td>
<td>39</td>
<td>82</td>
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<tr>
<td>July</td>
<td>0.07</td>
<td>0.10</td>
<td>0.03</td>
<td>6.8</td>
<td>10.2</td>
<td>3.0</td>
<td>104.1</td>
<td>232.7</td>
<td>21.8</td>
<td>67.8</td>
<td>198.6</td>
<td>0.2</td>
<td>40.5</td>
<td>51.5</td>
<td>24.5</td>
<td>4.8</td>
<td>5.1</td>
<td>52</td>
<td>99</td>
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<tr>
<td>August</td>
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<td>0.08</td>
<td>0.03</td>
<td>6.9</td>
<td>8.1</td>
<td>3.5</td>
<td>85.1</td>
<td>138.7</td>
<td>35.6</td>
<td>52.7</td>
<td>105.9</td>
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<td>36.6</td>
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<td>4.4</td>
<td>4.9</td>
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<td>78</td>
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<tr>
<td>September</td>
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<td>0.07</td>
<td>8.5</td>
<td>10.2</td>
<td>6.9</td>
<td>100.6</td>
<td>208.8</td>
<td>43.9</td>
<td>68.4</td>
<td>172.7</td>
<td>19.4</td>
<td>30.7</td>
<td>37.2</td>
<td>25.2</td>
<td>3.4</td>
<td>3.8</td>
<td>37</td>
<td>56</td>
</tr>
<tr>
<td>October</td>
<td>0.11</td>
<td>0.12</td>
<td>0.09</td>
<td>11.1</td>
<td>12.5</td>
<td>9.0</td>
<td>146.2</td>
<td>351.5</td>
<td>54.4</td>
<td>122.4</td>
<td>336.3</td>
<td>32.1</td>
<td>24.9</td>
<td>28.9</td>
<td>21.4</td>
<td>0.0</td>
<td>0.0</td>
<td>22</td>
<td>41</td>
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<tr>
<td>November</td>
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<td>0.12</td>
<td>0.10</td>
<td>11.7</td>
<td>12.6</td>
<td>10.0</td>
<td>105.7</td>
<td>166.1</td>
<td>43.2</td>
<td>87.2</td>
<td>148.3</td>
<td>23.9</td>
<td>16.4</td>
<td>19.4</td>
<td>13.0</td>
<td>0.0</td>
<td>0.0</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>December</td>
<td>0.12</td>
<td>0.13</td>
<td>0.11</td>
<td>12.6</td>
<td>13.3</td>
<td>10.7</td>
<td>108.9</td>
<td>115.6</td>
<td>96.5</td>
<td>95.9</td>
<td>103.5</td>
<td>82.8</td>
<td>13.2</td>
<td>15.6</td>
<td>10.7</td>
<td>0.0</td>
<td>0.0</td>
<td>12</td>
<td>14</td>
</tr>
</tbody>
</table>

Note: All values are mm except stormwater retained (%)
When the eight year model results are combined with rooftop area the potential stormwater reduction for a region can be estimated. Here, we apply the model to downtown Portsmouth, NH to obtain a volumetric reduction of stormwater. For the downtown Portsmouth study site, ArcMap 9.3 was used to quantify rooftop area. Aerial photographs were used in conjunction with ArcMap to identify flat rooftops (www.bing.com). The Portsmouth site has a total area of 340,000 m². There are approximately 219,000 m² of rooftop area, of which 51,000 m² (23% of rooftop area and 15% of total area) have flat rooftop space (Figure 4-18). Heating ventilating and air conditioning (HVAC) rooftop systems reduce the potential area for vegetated roofs. To account for the HVAC, the total flat rooftop area was reduced by 5% per building (Personnel Communication with Jared Markham). The total roof area that that can potentially support vegetated roofs is 48,000 m² (22% of rooftop area).
Table 4-7 provides average volumetric reductions for the downtown Portsmouth study site. Monthly volumetric reductions ranged from 12 to 38% based on the historic model results. August has the highest percent stormwater reduction (38%). July has the
highest volumetric reduction (1,751 m³). Months of high precipitation, such as April and May, may be more of a concern for municipalities. For the months of April and May, potential stormwater reductions are 1,471 and 1,612 m³, respectively, on average. From these findings, the city of Portsmouth could expect approximately 15,000 m³ of stormwater reduction per year if all flat rooftops were covered with vegetated roofs.

Table 4-7: Average values on a monthly and yearly basis from a vegetated roof flat rooftop area of 48,000 m² (non-winter months italicized). (1/1/2002 – 12/31/2009)

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation (mm)</th>
<th>Runoff (mm)</th>
<th>Stormwater Retention</th>
<th>Water Retained (mm)</th>
<th>m³</th>
<th>gallons</th>
<th>ft³</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>65</td>
<td>54</td>
<td>18%</td>
<td>11</td>
<td>554</td>
<td>146,222</td>
<td>19,547</td>
</tr>
<tr>
<td>February</td>
<td>79</td>
<td>62</td>
<td>21%</td>
<td>16</td>
<td>782</td>
<td>206,606</td>
<td>27,619</td>
</tr>
<tr>
<td>March</td>
<td>93</td>
<td>68</td>
<td>27%</td>
<td>25</td>
<td>1,199</td>
<td>316,795</td>
<td>42,349</td>
</tr>
<tr>
<td>April</td>
<td>136</td>
<td>105</td>
<td>22%</td>
<td>30</td>
<td>1,471</td>
<td>388,596</td>
<td>51,948</td>
</tr>
<tr>
<td>May</td>
<td>152</td>
<td>118</td>
<td>22%</td>
<td>33</td>
<td>1,612</td>
<td>425,840</td>
<td>56,926</td>
</tr>
<tr>
<td>June</td>
<td>112</td>
<td>76</td>
<td>32%</td>
<td>36</td>
<td>1,750</td>
<td>462,306</td>
<td>61,801</td>
</tr>
<tr>
<td>July</td>
<td>104</td>
<td>68</td>
<td>35%</td>
<td>36</td>
<td>1,751</td>
<td>462,677</td>
<td>61,851</td>
</tr>
<tr>
<td>August</td>
<td>85</td>
<td>53</td>
<td>38%</td>
<td>32</td>
<td>1,561</td>
<td>412,306</td>
<td>55,117</td>
</tr>
<tr>
<td>September</td>
<td>101</td>
<td>68</td>
<td>32%</td>
<td>32</td>
<td>1,552</td>
<td>409,869</td>
<td>54,792</td>
</tr>
<tr>
<td>October</td>
<td>146</td>
<td>122</td>
<td>16%</td>
<td>24</td>
<td>1,149</td>
<td>303,497</td>
<td>40,572</td>
</tr>
<tr>
<td>November</td>
<td>106</td>
<td>87</td>
<td>17%</td>
<td>18</td>
<td>889</td>
<td>234,811</td>
<td>31,390</td>
</tr>
<tr>
<td>December</td>
<td>109</td>
<td>96</td>
<td>12%</td>
<td>13</td>
<td>629</td>
<td>166,148</td>
<td>22,211</td>
</tr>
<tr>
<td>Non-Winter Months</td>
<td>700</td>
<td>505</td>
<td>28%</td>
<td>194</td>
<td>9,375</td>
<td>2,476,494</td>
<td>331,059</td>
</tr>
</tbody>
</table>
4.3 Sensitivity Analysis

A sensitivity analysis was conducted to determine the model’s sensitivity to the five vegetation and soil parameters. Each parameter was adjusted independently of the others to determine the change in stormwater retention percentage for the eight year historic period, but only the results for the non-winter months (May to October) are reported. The retention change when each parameter was varied by -50, -40, -30, -20, -10, 10, 20, 30, 40, and 50% of the original value is shown in Figure 4-19. The analysis showed that the model was not sensitive to the terms $Sh$ and $S_{Max}$. Increasing the crop coefficient and the $S_{fc}$ increases stormwater retention. An increase in $S^*$ decreases the stormwater retention. The response was nearly identical for c and $S_{fc}$. With the greatest retention decrease (from 28% to 16%) occurring for a 50% decrease in $S_{fc}$ ($S_{fc} = 0.1399$ to 0.0699 mm$^3$/mm$^3$).
Figure 4-19: Vegetation and soil parameter sensitivity analysis based on eight-year module results for non-winter months May to October.
Chapter 5 – Discussion and Conclusion

5.1 Comparison of Results to Previous Studies

The experimental goal was to quantify the water balance component of a vegetated roof system deployed on a roof. Here, we compare our findings to those from previous studies. Most studies including Palla et al. (2009), Villarreal and Bengtsson (2004), Hilten et al. (2008), and Gash et al. (2008) measured precipitation and runoff and assumed that ET would close the water balance. Four other studies have direct ET values that may be compared to my study. Table 5-1 summarizes the results from these previous studies.

<table>
<thead>
<tr>
<th>Author</th>
<th>Study Period</th>
<th>Location</th>
<th>Exposure</th>
<th>ET Min</th>
<th>ET Max</th>
<th>ET Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berghage et al. (2007)</td>
<td>2000-2003</td>
<td>Pennsylvania, USA</td>
<td>Greenhouse</td>
<td>0.2</td>
<td>2.5</td>
<td>1.15</td>
</tr>
<tr>
<td>Bengtsson et al. (2005)</td>
<td>July 2001 - July 2002</td>
<td>Augustenborg, Sweden</td>
<td>Roof</td>
<td>-</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td>Lazzarin et al. (2005)</td>
<td>Summer 02’ &amp; 03‘ Winter 04’</td>
<td>North-East, Italy</td>
<td>Roof</td>
<td>0.69</td>
<td>6.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Wolf and Lundholm (2008)</td>
<td>Oct. - Dec. 2007</td>
<td>Halifax, Canada</td>
<td>Greenhouse</td>
<td>0.5</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Sherrard and Jacobs</td>
<td>Aug. - Nov. 2009</td>
<td>New Hampshire, USA</td>
<td>Roof</td>
<td>0.1</td>
<td>2.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Note: ET values in mm/day

My ET results, while for the four month period, are comparable to other vegetated roof ET studies. While the 0.9 mm day$^{-1}$ average is lower than three studies, it is equal to Bengtson et al.’s (2005) value. My minimum ET valued, 0.1 mm day$^{-1}$, is lower than
the other studies. This may be due to limited measurement resolution as compared to my 0.051 mm resolution. Another possible reason is that the greenhouse studies limited the dry down period. Wolf and Lundholms’ (2008) controlled environment had less variability and values that fell well between other studies. Berghage et al. (2007) only provided ET results for two and ten days after a controlled watering for a single species of sedum. Accordingly, their maximum and minimum results were for days 2 and 10, respectively. Higher and lower values may have occurred outside of these provided days. While my maximum, 2.8 mm day$^{-1}$ is greater than that from both greenhouse studies, it is comparable to Berghage et al.’s (2007) maximum value of 2.5 mm day$^{-1}$. The only other study not performed in a greenhouse (Lazzarin et al. 2005) likely had higher values (6.9 mm day$^{-1}$) because of its location, local atmospheric conditions, a thicker soil medium, or an error in their energy balance.

These measurements were used to estimate crop coefficients for my study and Lazzarin et al.’s (2005). My study found an optimal crop coefficient of 0.53. This crop coefficient is constant for both stressed and non-stressed rooftop moisture conditions. ET reductions due to water stress are based on soil moisture depletions below wilting point. Lazzarin et al. (2005) found that the crop coefficient varied between 0.35 and 0.51 for summer periods without water stress. Rather than using a water depletion approach, they directly compared crop coefficients and found values from below zero to 0.35 for the stressed summer periods.

There are more experimental results from the runoff studies. The runoff retention from this research is reasonable, but on the low end of previously reported values (Table 5-2). Previous studies reported results as either an average of the individual storm
reduction percentage or as the total retained divided by total precipitation. The former is higher because there are more small storms with higher percent retentions which will give the same weight per storm as the fewer larger storms. This approach tends to skew results. For example, Teemusk and Mander (2007) found 88% reduction in stormwater based on two small events and one heavy event. Their limited number of events resulted in a deceptively high retention percentage. Stormwater reduction varies considerably among studies and is highly dependent on location, substrate depth, and roof slope. Depending on these conditions, reductions from 30 to 88% may be obtained. This research obtained an overall reduction of 32% and an average reduction per storm of 57%. Intercomparisons need to differentiate between overall reduction, and an average reduction per storm. When a percent reduction is found for each storm, the average percent reduction is generally higher.
Table 5-2: Comparison of experimental retention rates from vegetated roofs.

<table>
<thead>
<tr>
<th>Author</th>
<th>Study Period</th>
<th>Location</th>
<th>Slope (%Pitch)</th>
<th>Substrate Depth (cm)</th>
<th>Avg. Reduction</th>
<th>Avg. Per Storm Reduction</th>
<th>Sfc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bengtsson et al. (2005)</td>
<td>July 2001 - July 2002</td>
<td>Augustenborg, Sweden</td>
<td>0</td>
<td>3</td>
<td>46%</td>
<td>NA</td>
<td>30%</td>
</tr>
<tr>
<td>DeNardo et al (2005)</td>
<td>Oct. - Nov. 2002</td>
<td>Pennsylvania, USA</td>
<td>0</td>
<td>8.9</td>
<td>33%</td>
<td>45%</td>
<td>34%</td>
</tr>
<tr>
<td>VanWoert et al. (2005)</td>
<td>Aug. 2002 - Oct 2003</td>
<td>Michigan, USA</td>
<td>2</td>
<td>2.5, 4</td>
<td>70%, 71%</td>
<td>NA</td>
<td>20%</td>
</tr>
<tr>
<td>VanWoert et al. (2005)</td>
<td>Aug. 2002 - Oct 2003</td>
<td>Michigan, USA</td>
<td>6.5</td>
<td>4, 6</td>
<td>66%, 68%</td>
<td>NA</td>
<td>20%</td>
</tr>
<tr>
<td>Hathaway et al. (2008)</td>
<td>April 2003 - June 2004</td>
<td>North Carolina, USA</td>
<td>0</td>
<td>7.5</td>
<td>64%</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Getter et al. (2007)</td>
<td>April 2005 - Sept. 2006</td>
<td>Michigan, USA</td>
<td>2, 25</td>
<td>6</td>
<td>NA</td>
<td>85%, 75%</td>
<td>17.07 Mpa %</td>
</tr>
<tr>
<td>Sherrard and Jacobs</td>
<td>Aug. - Nov. 2009</td>
<td>New Hampshire, USA</td>
<td>0</td>
<td>10</td>
<td>32%</td>
<td>57%</td>
<td>14%</td>
</tr>
</tbody>
</table>
Getter et al. (2007) reported the highest average per storm reduction (85%). They attributed these high rates to differences in substrate depth, antecedent moisture conditions and precipitation patterns. In addition, they noted that other researchers included large storms in their stormwater analysis. Teemusk and Mander (2007) is the only other study with a greater average per storm reduction. As previously noted, this is because their study captured only three storms with percent retentions of 86, 94, and 22%. Had a greater variation of events been captured, their average percent reduction per storm would most likely have been lowered. Depending on slope, Villarreal et al.'s (2007) per storm reductions ranged from 29 to 53%. DeNardo et al. (2005) had a 45% average reduction per storm. These values, when compared to my 57% average reduction per storm are slightly lower. This is likely due to their shallower substrate depths.

The study with the greatest average percent reduction had the shortest research period and the fewest precipitation events (Teemusk and Mander 2007). VanWoert et al.'s (2005) 66 to 71% reduction was much higher than my study. Their site used a water retention fabric capable of holding 2 mm of precipitation placed below the substrate. This may contribute to the higher average retention achieved by the 6 cm substrate when compared to the 10 cm of substrate in this research. Hathaway et al.'s (2008) relatively high 64% reduction may also be due to additional drainage layers that add storage capacity as well as precipitation events that are more favorable to vegetated roof retention. Bengtsson et al.'s (2005) reduction of 46% and DeNardo et al.'s (2005) 33% reduction compare favorably to my results.
Frequency and magnitude of storms greatly affect stormwater retention. For example, Hathaway et al.'s (2008) 75% stormwater runoff reduction for a 23 mm storm did not indicate antecedent soil moisture conditions. The 75% retention exceeds the 10% retention achieved in this research for a 23 mm precipitation event with initial water storage of 13.71 mm. For a 4 mm substrate depth at 2% slope, VanWoert et al. (2005) achieved reductions of 97% for events less than 2 mm, 86% for events less from 2 to 6 mm, and 65% for events greater than 6 mm. My research had similar reduction for smaller events, 73% reduction for events fewer than 2 mm and an 82% reduction for events from 2 to 6 mm, but a lower, 35% reduction, for all events over 6 mm. Villarreal et al. (2007) performed simulated precipitation events using a sprinkler with initial soil moisture conditions at saturated field capacity making an accurate comparison difficult. Teemusk and Mander (2007) obtained 86% retention for a 2.1 mm event and negligible retention for a 12.1 mm event. My research obtained reductions between 0 and 100% for smaller events. While Getter et al. (2007) did not provided results for individual events, there were 16 light (<2 mm), 24 medium (2–10 mm), and 22 heavy (>10 mm) rain events with an average percent retention of 85% for a 2% slope.

The reviewed studies' used differing soil media. Most studies that report $S_{fc}$ values only present results from laboratory tests. In contrast my $S_{fc}$ value was optimized to predict drainage. $S_{fc}$ values range from a low value in my research, 14%, to a high of 34% in Bengtsson et al. (2005). As shown in the sensitivity analysis for my model, $S_{fc}$, is the second most sensitive parameter for retention prediction. Bengtsson et al. (2005) demonstrates a relatively high percent retention for only 3 cm of substrate depth. This demonstrates how variations in substrate can drastically affect stormwater retention.
Another difference among studies is the overall system that was monitored. The research reviewed in the Table 5-2 studies calculated the total stormwater reduction for an entire rooftop drainage system. This means that, in addition to vegetation and soil medium, these studies' reductions included all water retention when draining from the vegetated roofs. Reduction can occur in fabric layers placed below vegetated roofs, on the roof itself, and in pipes en-route to the systems monitoring runoff. Reductions in my research are obtained solely from the vegetated roof media itself with no additional reductions. Thus, my values represent a minimal retention improvement capable of this vegetated roof technology.

While many of these experiments have similar experimental methods, each study is inherently different and it is difficult to directly compare studies. Factors that differ among sites are substrate depths and composition, roof slopes, plant species, and extent of plant propagation. As seen in the sensitivity analysis, many of these factors significantly impact reduction. Some factors, such as plant propagation and species were not documented. A critical difference is whether the system is modular or plant-in-place. To date, no research has directly compared plant-in-place to modular systems. I recommend that studies completely document observation period, location, substrate depth and composition, roof slope, plant species and propagation, and whether the system is modular or plant-in-place. Event depth, event duration, event time to peak, and antecedent moisture conditions prior to each event should be reported.
5.2 Comparison of Vegetated Roof Models

My model successfully predicted the soil moisture storage to within 0.61 mm after a period of 115 days. When run with the long term historic data, 1/1/2002 to 12/31/2009, the model predictions were within 1 mm of observed data. The model, requires three vegetation parameters and two soil characteristic, but is most sensitive to c, $S^*$ and $S_{fc}$ parameters. Thus, it is highly transferable. The soil characteristics should be able to be determined from laboratory tests. The vegetation parameters are likely transferable for similar sedum species, but experiments are required to determine parameters for other species.

Experimental results show that storage increased as the year progressed. This may occur when there is an increase in storm event frequency, a reduction in daily temperature (and therefore ET) and a reduction in the plants’ transpiration rates. To account for this observed storage increase, the saturated field capacity ($S_{fc}$) was increased at the beginning of October. It appears that when a vegetated roof module is relatively wet, it is capable of holding more water. During dry periods, the soil may become slightly hydrophobic and store relatively less precipitation. It is important to note that the early summer months were not observed. Additional experimental data will refine the coefficients. Summer crop coefficients are likely higher and would increase ET and stormwater retention.

When comparing the current model to other models, key issues are the model time period, model versatility, parameter requirement, and runoff prediction performance. Model versatility refers to the ease with which a model can be applied to at other locations with different roof characteristics and climatic conditions. Lazzarin et al.'s
(2005) model predicts vegetated roof ET provided atmospheric data and can be run for any location. Their primary drawbacks are that ET rather than drainage is modeled, the model requires over 20 parameters, and the accuracy, which is only provided in visual interpretation, appears to be highly variable.

Berghage et al.’s (2007) AGRR model requires only one coupled soil and plant parameter, can be applied at multiple scales and locations, and predicts daily available storage. This relatively simple model achieved R² values of 0.578 and 0.679 at two separate locations when comparing predicted and observed runoff depths.

Berghage et al.’s (2007) SGRR is a flood routing based model that predicts vegetated roof retention on a per storm basis. While this model has few inputs and achieved an R² = 0.906, it requires high resolution rainfall hyetographs for each storm in addition to antecedent conditions including the month of the year and the number of days since the last storm. This limits the model to a short time period and makes it difficult to run continuously. Another individual storm runoff model, HYDRUS-1D, created by Hilten et al. (2008), also utilizes hyetographs and sets the soil moisture to 0.1 (the average soil moisture observed at the study site). Their model performs as well as SGRR (R² = 0.92), has 4 required parameters and similar limitations as SGRR. Palla et al.’s (2009) SWMS_2D runoff prediction model has over ten parameters and requires the user to input moisture content as an initial condition. While having low relative percent deviations, at times the model overestimates runoff by up to 33% and is limited to an individual storm basis.

Comparatively, the model created for this research is capable of running at a daily time scale for any duration provided that atmospheric data are available. Accuracies of
R² = 0.94 for module storage and R² = 0.98 for drainage exceed the other studies. Overall, this model compares favorably to previous models. It is recommended that the model be validated at other sites and additional experimentation conducted to determine summer crop coefficient values.

Carter and Jackson (2007) performed a spatial analysis for a watershed in Athens, Georgia to determine impervious area and flat rooftops. They found that rooftops accounted for 16% of total land cover within the watershed with 47% of rooftops being flat as compared to the 14% and 22% values in my Portsmouth area. Within their commercial downtown region 25 to 85% of the rooftops were flat. A curve number model performed for this study showed that even with widespread use of vegetated roofs within the watershed that stormwater reduction was minimal for larger events. However, events below 2.54 mm had a noticeable effect on the recommended treatment volumes across the watershed (Carter and Jackson 2007).

5.3 Limitations

5.3.1 Research Limitations

The lysimeter approach used in this research builds upon a previous design used in a greenhouse by Berghage et al. (2007). On a roof environment, the lysimeter performed extremely well and the required observations were made consistently at high resolutions. However, some limitations of the lysimeter approach are that air flows below the module and that it is difficult to determine the module drainage. The module is suspended above the roof which enables air flow above and below the module. A vegetated roof would be placed directly on a surface and the elevation may affect the
module’s soil temperature. The surrounding roofing material, which differs from vegetated roof cover, may also affect the temperature because of the edge effects. Changes to the soil temperature may affect ET rates. Ideally, the modules being weighed would be surrounded by other modules placed on the roof. While shading from the north and south wall likely affected the ET rates, shading is a common occurrence in urban areas and should not be considered a limitation, but needs to be documented as a potential variable.

An additional research limitation is the inability to separate evaporation and transpiration in the water balance. This separation is needed to differentiate the role of plants versus soil media in a vegetated roofing system. A possible approach would be to compare modules with vegetation and without vegetation. A challenge is that removing vegetation would likely increase soil evaporation. However, because the goal was to document water losses to the atmosphere rather than the specific process by which those losses occur, the inability to differentiate is not a source of error for the water balance.

Drainage is not recorded directly. For certain storms, precipitation rapidly drained during much of the storm. At times, it was difficult to determine when drainage ended. Improved drainage estimates are recommended via additional monitoring which might include video or runoff collection. The lack of direct drainage observations limit the accuracy of drainage results. Future research with coincident drainage observations are required to quantify errors.
5.3.2 Model Limitations

In order to apply this research in practice, a full year of data is needed. The data gathered from August to November are only representative of those periods and differences are anticipated during the remaining summer months (May, June and July). While soil parameters are unlikely to differ during the summer, it is possible that vegetation parameters differ seasonally. Crop coefficients vary over the growing season for each plant and typically peak during the summer. Because the majority of my research period was during the late season for sedums, it is likely that the crop coefficient was underestimated during midsummer. If this is the case, a higher stormwater reduction would result.

The model solves the water balance on a daily time step. For many applications this is a sufficient time step to predict vegetated roof storm event retention. However, daily variations cause error in the predicted values. For instance if the model was run for a shorter time step, it could capture the ET between events on the same day.

The model performs well for both drainage and storage predictions. However, the prediction of ET is not as accurate. While the results indicate that the model predicts ET well enough to accurate for drainage and storage, an improvement in ET prediction might improve the model. Other methods to estimate $ET_0$ the Penman-Monteith equation may be readily adapted to these types of studies and potentially reduce ET prediction errors.

The regional model uses all the flat rooftop are in the downtown Portsmouth, NH site, witha 5% reduction for HVAC systems, for roof area capable of holding vegetated roofs. Structural capabilities of buildings were not considered in this area estimated but are critically important to determining viable vegetated rooftop space. Many buildings
throughout New England are capable of holding additional weight because snow load factors of safety are relatively high. This is not true however for all buildings. It is likely that including structural capacity would reduce the potential vegetated rooftop area.

This approach has taken a physically-based crop scale model approach and applied it at a scale that is practical for engineering design. Traditionally these different modeling approaches are not integrated. Therefore, while this approach removes many of the weaknesses and error from engineering scale hydrologic models, it also incorporates those from the physically based approach.

5.4 Conclusions

While quantitative vegetated roof stormwater performance has been studied previously, this is the first lysimeter-based approach performed outside of a greenhouse. ET, drainage, and storage characteristics of vegetated roofs have been explored in previous studies with ET as the estimated residual term (Bengtsson et al. 2005; Lazzarin et al. 2005; Berghage et al. 2007; Wolf and Lundholm 2008). This study provides the first detailed understanding of water storage dynamics for a vegetated roof as well as ET measurements. This high resolution water balance included both measured ET and dew formation, an aspect of the water balance that has not been considered in other vegetated roof research. The experimental results had an average stormwater runoff reduction of 32% and an average reduction per storm of 57% for the 4 month research period. This assessment of vegetated roof performance in Seacoast New Hampshire will provide municipalities with a quantitative means of estimating stormwater reduction.

An important vegetated roofs performance metric is their ability to retain stormwater. In order to broadly apply the experimental values, a model was created to
predict long term water storage for vegetated roofs. Previous models have been created (e.g., (Lazzarin et al. 2005; Berghage et al. 2007; Hilten et al. 2008; Palla et al. 2009) but few are capable of predicting long term storage and are readily applied to different sites. The model performs extremely well with high accuracies and efficiencies for drainage ($R^2 = 0.98$, $E = 0.98$) and storage ($R^2 = 0.94$, $E = 0.93$) and requires limited parameterization.

This model was readily used to assess vegetated roof performance in Seacoast New Hampshire and to provide municipalities stormwater reduction estimates. The percentage of vegetated rooftop space with respect to total flat roof area and total study area was determined to be 22% and 14%, respectively. Application of vegetated roofs to downtown Portsmouth has the potential to reduce stormwater by approximately 4,000,000 gallons (15,000 m$^3$) annually. In combination with local officials with wastewater treatment plant information, this information can be used to determine the usefulness and cost savings provided by the vegetated roofs.

5.5 Future Research

Future research would benefit from additional improved observations. While my lysimeter approach provided highly accurate ET values, it was difficult to determine when drainage began and ended. Stormwater runoff collection from the modules, coupled with visual monitoring of rain events, would provide a more accurate understanding of the drainage performance. In addition, wind may have affected the temperature profile within the soil medium. If so, a protective barrier surrounding the
module might be beneficial. A temperature comparison to a module directly or roof would indicate if a difference exists.

Future research should include a larger scale study that would eliminate edge effects at the site by using a completely covered vegetated roof system. This would also allow for replication of the lysimeter measurements and additional monitoring as recommended above. In addition, comparison among vegetated roofs, soil medium (without plants), and a traditional, control roof would add insight and provide the observations needed to refine the model. With these comparisons, it would be possible to determine what role plants play in enhancing storage capabilities through transpiration. Lastly, an understanding of vegetated roofs performance in freezing (or winter) conditions is needed. A study could be designed to monitor runoff retention and snowmelt.
References


Appendix A: Moisture Content Calibration Equations

2.304 mV = 10 % Moisture Content  
(Moisture Content Calibration  
Equation 1)

1 mV = 37883 g  
(Moisture Content Calibration  
Equation 2)

\[ \theta = 0.10 = \frac{V_w}{V_{tot}} \]  
(Moisture Content Calibration  
Equation 3)

\[ V_w = 0.10 \times V_{tot} = 7511 \text{ cm}^3 \]  
(Moisture Content Calibration  
Equation 4)

\[ V_w = A \times \text{Depth of Water} \]  
(Moisture Content Calibration  
Equation 5)

\[ \text{Depth of Water} = \frac{V_w}{A} = 10.2 \text{ mm} \]  
(Moisture Content Calibration  
Equation 6)
Depth of Water = \frac{grams - y}{g \rightarrow mm\ Conversion} \quad (Moisture Content Calibration \ Equation 7)

y = grams - (Depth of Water \ast mm\ Conversion) \quad (Moisture Content Calibration \ Equation 8)

Moisture Content (\theta) is the percent moisture within a given soil sample and is equal to the volume of water (Vw) over the total volume of the sample (VTot). The area of the module (A) refers to the surface area that is parallel to the ground and capable of capturing precipitation. The laboratory tested dry weight of the module is described by the term “y” and is the ultimate goal of the soil moisture calibration.