ABSTRACT

Title of Document: EVALUATING THE FEASIBILITY OF IMPLEMENTING A GREEN ROOF RETROFIT ON PITCHED RESIDENTIAL ROOFS

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Green roofs are one solution to stormwater runoff which is a major environmental problem. However, the majority of green roofs are primarily implemented on flat roofed commercial buildings and not residential homes with sloped roofs. Team SO GREEN designed a light-weight green roof system retrofit for residential homes. Between June and November 2014, green roof performance data was collected and compared between the designed sloped roofs and a non-sloped control. The sloped design performed well and one test slope was improved with a recirculating irrigation system. An economic analysis was made and a focus group determined preliminary consumer interest, aesthetic preferences, and barriers. This study enriches the body of knowledge regarding bringing green roof systems to the residential home market.

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By

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Introduction

Current practices of rapid urbanization are harmful for humans, animals, and overall ecological balance. As new housing and commercial developments are built, they replace trees and other vegetation with buildings and roads that do not absorb rain water. These surfaces are considered to be "impervious." Impervious surfaces increase stormwater runoff, which delivers pollutants into major waterways, washing sediment and chemicals from urban areas into streams and rivers (Thurston et al. 2008). Pollution is environmentally taxing and is also a major financial burden. Water polluted by toxic chemicals, accumulated sediment, and excess nutrients cost Maryland residents $196 million in 2011 (Green Maryland 2012). Perhaps most alarming stormwater runoff is now an ever more prevalent problem in residential areas as the number of paved surfaces and housing developments increases with burgeoning human populations.

Stormwater runoff causes problems in many cities, like Baltimore, MD and Washington, D.C. Many cities have combined sewer systems that collect sewage and rainwater in a single channel. The collected sewage and rainwater is sent for treatment at a wastewater treatment facility before being released back into natural waterways. When the amount of rainfall during a rain event is below ½", the system functions well; however, larger rain events or periods of prolonged precipitation cause combined sewage overflows (CSOs). During these larger rain events, stormwater treatment facilities often exceed capacity and cannot treat the high volume of waste. Both untreated stormwater and raw sewage are released into natural waterways. On an average day, the Blue Plains Advanced Wastewater Treatment Plant sees more than 330 million gallons of sewage (DC Water 2015), but during rainfall this number could overload the plant's 370 million gallon capacity, causing it to overflow.

Green roofs are a proven mitigation technique to stormwater runoff and erosion problems because of their ability to absorb rainfall (VanWoert et al. 2005). Most homeowners, though, have been unable to implement green roofs because the majority of existing designs are for flat roofs, not conducive to the pitched roofs found on most residential homes. Pitched roofs have a low tolerance for weight, making it difficult to implement a fully functional green roof system.

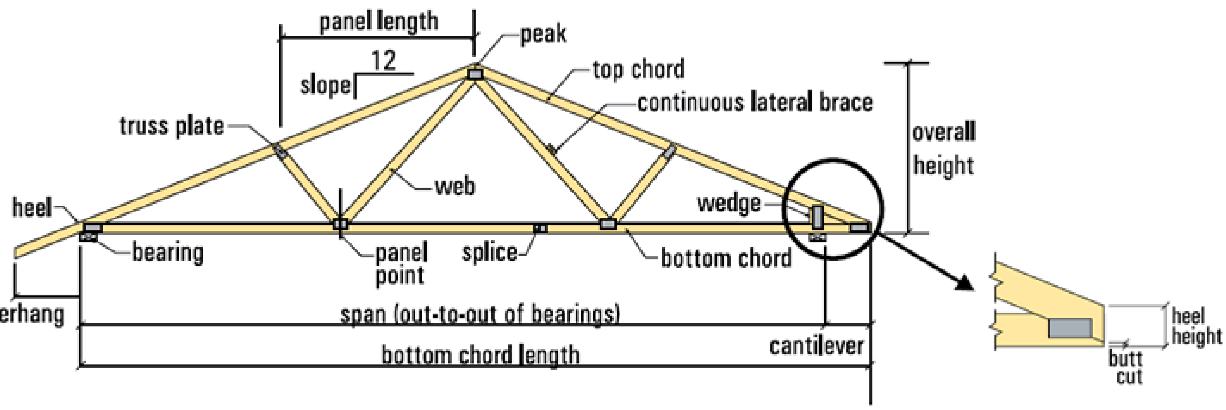

Figure 1. Truss Configuration (Anand 2008)

Currently, there are some mitigation techniques for storm water runoff. Rain gardens, wetlands, and cisterns are solutions that homeowners can use to manage their stormwater; however stormwater management in suburban areas is still a major problem because of the lack of other easily implementable solutions.

In order to improve stormwater management and erosion in suburban areas, Team SO GREEN investigated green roof designs to create a lightweight retrofit for homes with pitched roofs. Through experimental research, the team worked to answer the question "How can team SO GREEN design the best retrofit green roof to be placed on existing sloped roofs?" The team defined the "best" retrofit design as one that minimizes additional deadweight load to roofs, mitigates stormwater runoff, and appeals aesthetically to homeowners seeking sustainable home modifications. Team SO GREEN planned to design a retrofit green roof with a dead load of 10 pounds per square foot or less, while maintaining stormwater retention capabilities comparable to previous studies of sloped green roofs (VanWoert et al. 2005). The team hoped that homeowners would invest in the idea of a sloped retrofit green roof as a viable option to combat excess stormwater runoff and erosion.

SO GREEN conducted a series of focus groups to explore the marketability of green roof installation. This aimed to answer the questions, “How interested are Maryland homeowners in implementing green roof technology on their homes,” and “What is the appeal of a green roof for homeowners?” The team anticipated that the focus group would provide essential information to guide the design to make it more marketable and homeowner friendly. The team incorporated this homeowner feedback in the financial, social, and aesthetic considerations of green roof design.

This paper provides a literature review of existing methodologies and studies in order to show the gaps in previous research that this project sought to fill. In addition, this thesis explains team SO GREEN’s research design for the experimental portion of the project and outline the focus group process. It explains the team’s data collection and analysis methods as well as provides a detailed summary of results. This paper concludes with a discussion of the results obtained, the limitations encountered in this study, and recommendations for future research.

Literature Review

This literature review will introduce the research problem, provide a historical look at the development of green roofs with particular attention to applications of green roofs in more recent history, and overview the benefits and current applications of green roofs. The literature review will highlight the limits of application in the past, in order to show ways in which green roof application can be extended. This section particularly emphasizes the gap in research that SO GREEN’s study fills. A major portion of the literature review will explore the environmental and psychological benefits of green roofs, as well as the economic considerations when using green roofs.

Green roofs are broken into two categories: extensive and intensive. An extensive green roof has a substrate layer of less than 6 in., making it lightweight (Getter and Rowe 2006). It uses a palette of plants often made up of Sedums and other succulents (Magill 2011). Intensive green roofs use a thick layer of substrate, normally greater than 6 in., and can often act as a garden (Getter and Rowe 2006). Trees and other large plants may be used on intensive green roofs. The literature review will focus solely on extensive green roofs.

Components of a Green Roof

A green roof is an engineered system which can serve many purposes such as mitigation of stormwater runoff, energy savings through insulation, temperature control, and aesthetic appeal. The green roof is made up of several layers. Typically, these layers include insulation, a waterproof membrane, a membrane protection layer, a root barrier, a drainage layer, a filtration layer and then the substrate where plants grow (Magill 2011).

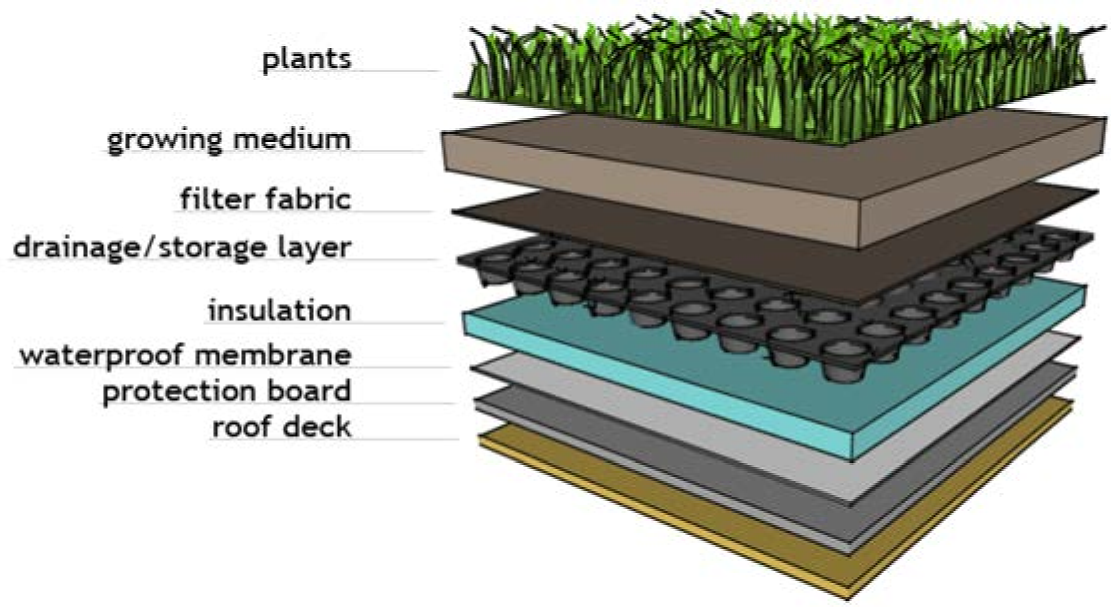

Figure 2. Example Green Roof Layers

Source: http://www.greengarage.ca/greenroofs/features.php

Substrate

Substrate, the engineered soil used for green roofs, is an integral part of the green roof system. The choice of substrate, with regards to physical composition and depth, affects weight of the green roof, retention of rainwater, and plant growth. A well-engineered substrate will facilitate water movement, allow plants to establish deep roots, and withstand a variety of conditions, including extreme heat, extreme cold, wind, rain, and snow. A poor substrate choice can hold too much or too little water and kill plants or cause structural stress due to excessive weight. This section will discuss the composition of substrate and its importance in terms of optimizing the performance of a green roof.

Substrate, or growing media, is a mix of organic matter and mineral components (FLL 2002). The mineral components, or the inorganic matter, may consist of slate, pumice, crushed brick, expanded shale, or other materials broken down into a variety of particle sizes (Magill 2011). The ratio between organic and inorganic matter is important because it influences plant growth and water retention. Plants need sufficient organic matter to grow so they have nutrients; however, organic matter often has small particle sizes, which can clog the spaces between the larger inorganic particles and cause too much water retention. Smaller particle sizes in the inorganic portion of the mix can also result in excessive water retention. Too much water retention results in soggy media in which plants cannot survive. Nagase and Dunnett (2011) conducted a study varying the ratio between organic and inorganic material and concluded that a mixture with ten percent organic matter, by volume, is optimal for plant growth. Team SO GREEN used the results of this study when testing substrate mixes.

The weight of a green roof system is a major concern, especially when implementing a green roof on an already-existing building that has a pre-determined load bearing capacity. There are two weights to consider: dead and live loads. The materials of the system that are always present – the green roof components – make up the dead weight, or the weight of the roof in normal conditions. Any additional weight such as leaf debris, rainwater, or snow, make up the live load. The building structure must be able to support varying live loads. In natural circumstances, there is very little opportunity to control the live load on a building. Instead, the dead weight can be manipulated, and in this case decreased by minimizing the weight of the green roof components, most notably the substrate.

The dead load can be reduced in several ways, but the component that will have the biggest effect is the substrate. Use of lighter substrate materials, and the depth of the substrate can drastically reduce the dead load of a given green roof. The depth of substrate in an extensive green roof can be up to almost 6.0 in. or 15.2 cm. (Magill 2011) and as low 2.5 in. or 6.4 cm. (TipThePlanet); however, a study by Getter and Rowe (2008) determined that both flat and pitched roofs function best with a substrate depth of 2.75 in. to slightly below 4.0 in., or 7.0 to 10.0 cm.

Plant Species

Plant selection for green roofs is another integral aspect of the green roof system since having a healthy and attractive vegetation layer is the goal of many designers. The vegetation layer helps mitigate urban heat island effect, improve air quality, replace lost natural landscape, and enhance biodiversity (Alexandri 2008). Most importantly, plants provide the basis for the mitigation of stormwater runoff that a green roof seeks to achieve through the retention and evapotranspiration processes (Bianchini and Hewage 2012). Green roof plants are selected because they are able to survive harsh environmental conditions, including summer droughts, extreme heat, high winds, freezing temperatures, and snowfall (VanWoert 2005). Moreover, green roofs are ideally self-sustaining systems that require minimal maintenance, such as irrigation. As a consequence, the vegetation layer as well as the media layer must be carefully studied and designed to optimize hydrology, minimize weight, and be resilient.

To this end, Bianchini and Hewage (2012) recommended Crassulacean Acid Metabolism (CAM) plants for green roofs. CAM plants can conserve water under drought conditions by opening their leaf pores to exchange oxygen and carbon dioxide in the evening. This characteristic enables CAM plants to survive through harsh environment. Sedum plants are CAM cycling plants that have proven to be effective; Butler and Orians (2011) found that Sedum plants are one of the most beneficial plants for green roofs because they are self-sustaining, grow rapidly, and have a high ground cover density. With proper species selection, Sedum plants can tolerate extreme temperatures, high winds, and a limited water supply, storing enough water in their roots to last up to 88 days of drought (Rowe et. al. 2014). Succulent plants, like Sedum species, have been documented as being able to tolerate the extreme conditions on rooftop environments (Getter and Rowe 2006).

The purpose of green roofs goes beyond just the fulfillment of engineering requirements to embrace dynamic ecosystems employing a diversity of plant species. The ecological literature provides some evidence that diverse green roof plantings are more productive than monocultures. Cook-Patton and Bauerle (2012) demonstrate in their paper that an increase in biomass in green roofs enhance several green roof services, such as ambient temperature cooling, roof insulation, and absorption of nutrient pollution. They also suggested that plant diversity in green roofs reduce the plant community's susceptibility to environmental change, pests, disease incidence, and invasion by weeds. Therefore, green roof performance cannot be optimized with Sedum-only plant community; instead, researchers must select plant species from different genera known to survive on green roofs and determine which species mixture maximizes the performance of green roof.

Benefits of Green Roofs

Environmental/ecological benefits

Cities across the nation experience a plethora of environmental issues arising from increased development and urban expansion. Stormwater runoff, erosion control, and pollution are especially harmful to the environment in and around developed areas. In addition to these direct effects are unseen or distant externalities, including the loss of biodiversity, increased power consumption, and the urban heat island effect. Stormwater runoff from human development causes a variety of issues including combined sewage overflows (CSOs), erosion, and pollution. Green roofs reduce and slow the amount of stormwater that runs off impervious surfaces into waterways through increasing retention of water and evapotranspiration back into the atmosphere. This section will provide background on the aforementioned issues, how green roofs mitigate the issues through retention and evapotranspiration, and explain the focus Team SO GREEN's related research.

In many older cities in the United States, stormwater and sewage are directed through the same pipe system to water-treatment plants. This functions well under 0.5 in. (1.3 cm.) of rain, but rain events above 0.5 in. (1.3 cm.) cause these systems to overload (DC Water 2015). These large volumes of water overwhelm municipal wastewater treatment plants, resulting in the release of untreated and poorly treated sewage into surface water. Many communities along the Great Lakes shoreline, for instance, still use combined sewage and stormwater pipe systems and tens of billions of gallons of untreated sewage and stormwater are dumped into the lakes. In 2010, polluted runoff and stormwater, carrying pollutants from sewage and agricultural areas, caused 351 days of beach closings, due to health risks from the water (Lyandres and Lyman 2012).

In addition to stormwater runoff reduction, green roofs also remove carbon dioxide from the atmosphere. Estimates show that if twenty percent of capable buildings in D.C. had a green roof, airborne pollutants would be removed at a similar rate to the photosynthetic results of 17,000 planted trees (Rowe 2011). One concern with green roofs is the environmental cost of creating a green roof in terms of how energy intensive production of a green roof system can be; however, there are more environmental benefits than disadvantages of building green roofs (Bianchini and Hewage 2012).

Notably, green roofs conserve energy in poorly insulated buildings. Older homes and warehouses with green roofs experience a significant reduction in energy consumption for non-insulated buildings (Castleton et al. 2010; Bianchini and Hewage 2012; Jaffal et al. 2012). In research published by the National Research Council of Canada, they found that an extensive green roof reduced the daily energy demand for air conditioning by over 75% over the summer (Green Roofs for Healthy Cities 2015). Other studies indicated that green roofs reduced heat gain and loss in buildings while stabilizing temperature and lowering peak indoor temperatures by acting as an insulation layer (Martens et al. 2008; Castleton et al. 2010; Jim and Peng 2012).

Psychological Advantages

Beyond environmental benefits, the widespread adoption of green roofs brings forth issues in society surrounding psychosocial benefits and adoption trends. It is important to analyze the psychological effects of green roofs on humans in addition to the return rate and money saving potential on a roof with higher installation costs. Research on these topics will help Team SO GREEN determine whether homeowners will implement green roof technology, and what social and economic benefits affect the decision to install a green roof system.

In 1984, Edward O. Wilson proposed biophilia, a theory suggesting that humans have an inherent desire to connect with nature (Grinde and Patil 2009). This has very real psychological and economic implications. For example, living close to a park increases property values 15-25 percent due to the provision of greenery (Bianchini and Hewage 2012). Furthermore, White and Gatersleben (2011) found that houses covered in vegetation are more visually appealing than houses with standard roofs. They conducted a study where they presented one group of participants with photographs of houses with and without vegetation through an online survey and asked them to rate both houses. The investigators then interviewed a second group of participants, examining their preferences and installation concerns. Many participants found the ivy and meadow vegetation-covered roofs to be more aesthetically pleasing.

Furthermore, research by environmental psychologist Douglas McKenzie-Mohr found that the aesthetic appeal associated with green roofs is an important psychosocial benefit that has the potential to create added value beyond its ecosystem services (McKenzie-Mohr 2010). McKenzie-Mohr (2010) introduced Community Based Social Marketing (CBSM) as a framework for creating behavior-changing sustainable programming. He found through CBSM that behavior change is most effective when undertaken at a community level, because it involves direct contact with people and is effective at generating public awareness and understanding of sustainability issues. Green roof technology, like any other innovative movement, will therefore be more successful if it is implemented on a large scale, particularly with community buy-in.

Economic Considerations

In addition to social benefits, economic viability is necessary to convince homeowners to install green roofs (Claus and Rousseau 2012). Bianchini and Hewage (2012) determined that the maximum length of the payback period on a green roof for homeowner satisfaction is generally ten years. Another cost-benefit analysis states that the benefits of energy savings and a longer roof life balance the installation cost and maintenance fees associated with having a green roof (Claus and Rousseau 2012). Alternatively, a 2010 study of a 30 year life-cycle analysis of green roofs found that in the U.S., green roof costs exceeded their benefits. The researchers also stated the lack of standardization in the U.S. is cause for great variability between green roof systems, making general cost-benefit results inconclusive (Blackhurst 2010). However, since 2010, various stormwater taxes and mitigation programs have been implemented in a few localities which create greater economic incentive for homeowners and businesses to manage their stormwater. In Prince George's County, for instance, Maryland individuals building a green roof can receive up to $2,000 in rebates in addition to other state and federal rebates (Legislative Branch News 2012). Recent movements for increased incentives and industry standardization shows promise that cost-benefit ratio of green roof adoption can become favorable in the years to come.

Methods and Materials: Modules

In this chapter, Team SO GREEN will present its methodology for the experimental research, results of the research, as well as review the assumptions and limitations involved. To conclude this section, the team will present and discuss the results of the study.

Phase I: Creating an Ideal Substrate

As aforementioned, a proper substrate is an integral part to a successful green roof system. Phase I of the study was to design and test different substrates to determine the best composition of inorganic materials for the roofing system. For the design of the retrofit green roof, the team identified a few key components of an ideal substrate. First, a lightweight substrate is crucial. Standard residential homes have roofs that weigh 10 psf dead weight, and can support a further 40 psf of live weight (Hodgson 2012). Thus, a lightweight substrate is central in the development of a retrofit green roof. Second, the substrate must be able to retain sufficient water to facilitate plant growth and reduce water runoff. Therefore, the best substrate was determined based on four factors: weight, granulometric distribution, durability, and plant tolerance. Weight would be decided from hypothesizing the overall weight of the substrate per square foot, assuming at least a 2 in. depth. Granulometric distribution, which is the particle size distribution, would be determined by a sieve shaker in order to gauge the size composition. Durability, which is the substrate's ability to withstand through changing conditions without breaking down, would be tested by freeze-thaw tests. Plant growth, which is the plants' abilities to grow in the substrate, would be measured by sight and judging the amount of plant coverage.

The team decided to begin testing Growstone® (Growstone Albuquerque, NM), a synthesized substrate that is composed of recycled glass. Initially, the team tested three different mixes of substrate. Mixes 1 and 2 contained a 50/50 and 30/70 volumetric ratio of Growstone®

and organic matter (mushroom compost), respectively. These mixes were mixed using a concrete mixer to obtain an evenly distributed mix. Mix 3, the team's control, was an aggregate material made from Haydite and volcanic pumice. This mix, known as M2 (Stancills Inc, Perryville MD) is used in the Mid-Atlantic region as a green roof substrate. First, the team conducted a particle distribution test. A shaker moved the mixes through sieves of different sizes and organized the particles by size. It is crucial for substrate mixes to contain a certain ratio of large and small particles. If a mix contains too many large particles, all the water will run through the substrate, and if there are too many small particles, the particles will hold too much water. A roof with too much water can kill plants and is also very heavy.

Second, the team tested the three mixes with thirty-day freeze-thaw tests, which would determine Growstone's ability to withstand the constant shrinking and expanding due to temperature change that substrates may experience in variable outdoor weather conditions. This test was never completed, though, because the team observed that the plants were not performing well in the Growstone.

Plant growth facilitation is an important aspect of a well-performing substrate. The team performed the plant growth tests in the Research Greenhouse Complex at the University of Maryland. The team used *Sedum kamschaticum* because, as found in literature and previous studies, *S. kamschaticum* is one of the most widely used plants for green roofs, grows easily and requires little maintenance. The plant also has large, visible leaves that make it easier to see if the plant is growing normally. *Sedum kamschaticum* was placed in twenty-one 4 in. pots, each containing one of the three mixes for a total of seven replicates per treatment. The pots were randomly placed on trays in the greenhouse with controlled temperature conditions of 70° F and equal hours of light and dark during the day. After two months of growing, the plants in mixes 1 and 2 began displaying brown around the edges of the leaves and the plants themselves were starting to wilt. Plants in Mix 3 with only the M2 mix were healthy.

Based on the results of these tests, the team found Growstone to be unfit and unusable for use on green roofs. After noticing the leaf edge necrosis in the plants, the team tested Growstone at the University of Delaware Soils Lab. It was determined that Growstone contained high amounts of sodium, which was assimilated into the plant, causing damage to leaf tissue. Also noted was that the Growstone particles were too lightweight and floated when saturated with water. This may have prevented plants from establishing their root systems. Lastly, and perhaps the biggest obstacle with Growstone was that the manufacturer discontinued the particle size for this project, so the team could no longer use and test this product.

As a result, the team ultimately decided to utilize a substrate containing M2, 15% Greek pumice (a type of porous volcanic rock), and a minimal amount of organic matter. The team was unable to thoroughly test this substrate mixture similarly to the Growstone due to lack of time, but previous research was done to ensure that the components of this mixture satisfied plant tolerance and durability goals (Griffin 2014). M2 with Greek pumice has been successfully used on several green roof projects, meaning that it has the capacity to facilitate plant growth (Ristvey 2012) and its components are easily attainable in the Mid-Atlantic region. Organic matter and Nutricote slow release fertilizer (Florikan ESA LLC, Sarrasota, FL) was used to provide nutrients to the plants. This substrate mixture containing M2, Greek pumice, and a minimal amount of organic matter properly satisfied the four factors of an ideal substrate. It was lightweight, durable, contained varying particle sizes, and facilitated plant growth.

Phase II: Building and Planting Modules

Phase II of the experimental design consisted of building four outdoor model roofs or modules. Table 1 shows the study timeline of construction and data collection. The modules were constructed to resemble the support structure of a residential roof. By conducting a brief literature review on traditional roof structures and consulting with Neal Hodgson, architect and owner of DC architecture firm Hodgson Architect, Inc., the team was able to design and construct four 12 ft. X 4 ft. modules that conform to traditional roof trusses. The four modules would test the performance of the design at varying slopes. There is one roof module at each of four different slope options: flat or 2º, 15º, 30º, and 45º. The 2º slope serves as the control (a common slope on "flat" green roofs). The 15º slope simulates ranch-style houses with roof grades averaging 4 to 12 (i.e., 4" vertical rise for each 12" of horizontal run). The 30º and 45º modules simulated two-story homes with average roof grades between 7 to 12 (30º) and 12 to 12 (45º) (Hodgson 2012).

Table 1. Module Timeline

ACTIVITY	START	FINISH	DURATION
Build Test Roofs	Oct-2013	Nov-2013	1 month
Plant Roof	Nov-2013	Nov-2013	2 weeks
Replant Roof	Jan-2014	Jan-2014	1 week
Growing Period	Feb-2014	May-2014	2 month
Data Collection VWC	May-2014	Nov-2014	6 month
Data Collection Runoff	Jun-2014	Nov-2014	5 month

Design plans for the modules are shown in Figures 3-6. The proper roof design for the modules was essential. An inadequate design could have dangerously compromised the structural integrity of the modules. Also, proper design would eliminate a variable in the team's research and make the data more accurate and applicable to sloped roofs. Roof framing functions as part of the roof diaphragm and supports the load applied to the roof. It plays a vital role in transferring the loads horizontally to the support walls below. The team accommodated the roof framing of the modules to support the minimum load-bearing weight of 50 psf. The team decided to use a Palladian truss structure for the roof framing, because that is the most common on residential roofs. Conveniently, trusses are simultaneously lightweight and strong. They are used in a variety of applications, so can be designed for any roof angles.

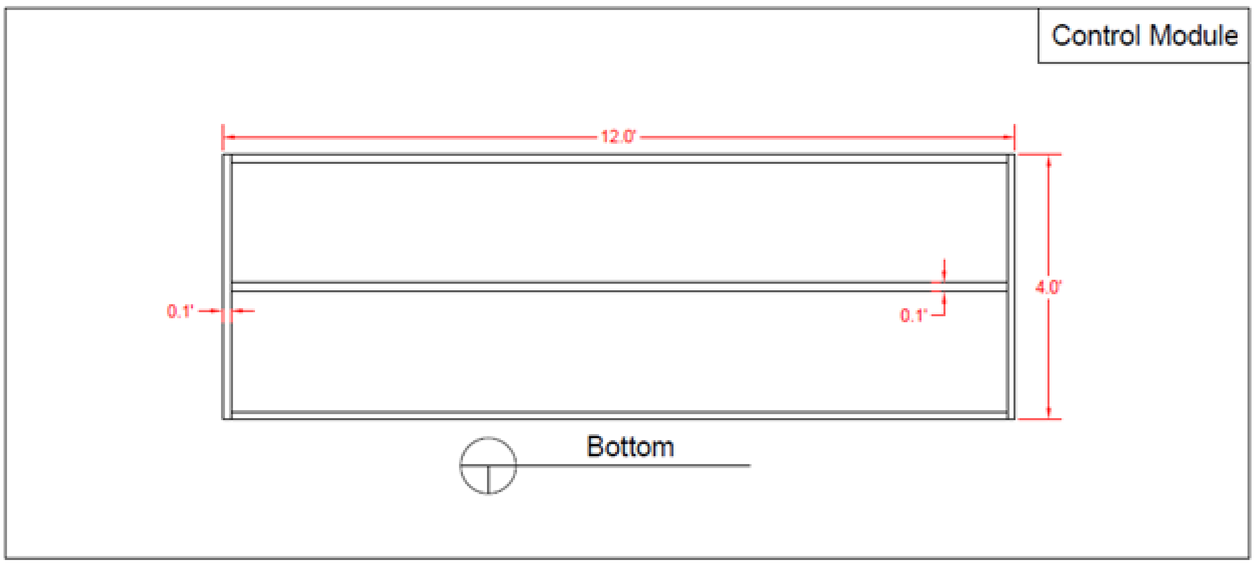

Figure 3. Control Module Design

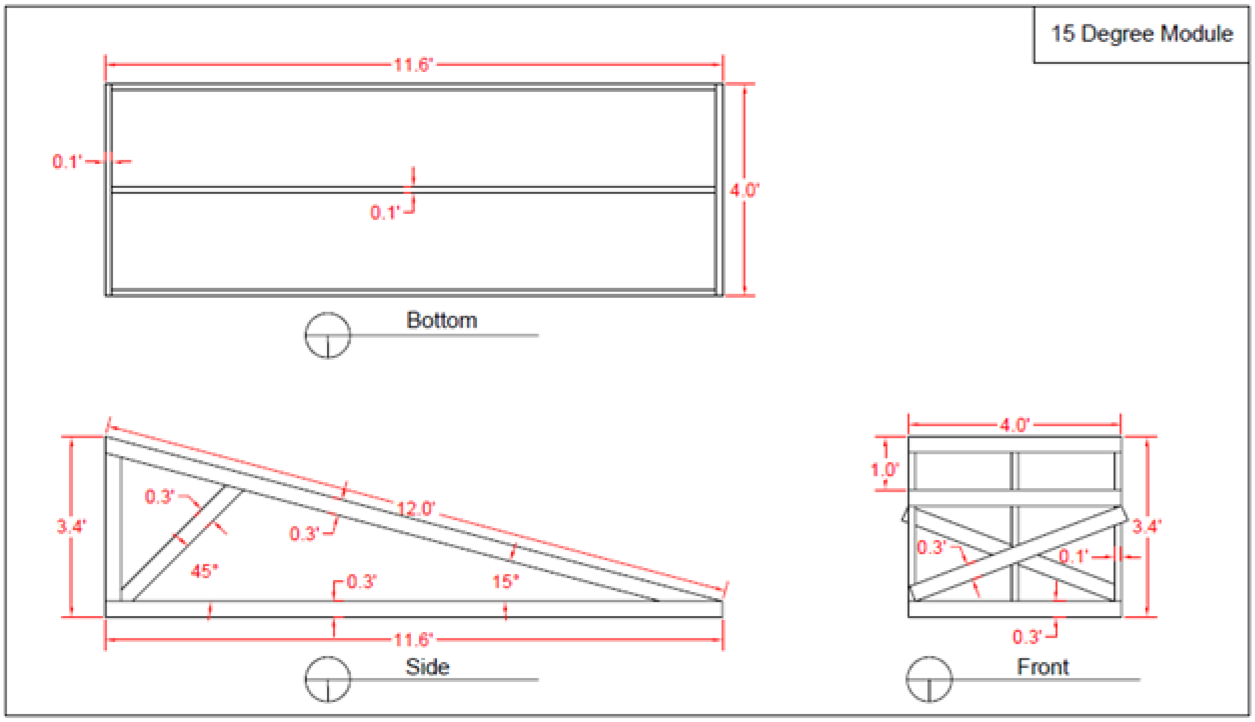

Figure 4. 15 Degree Module Design

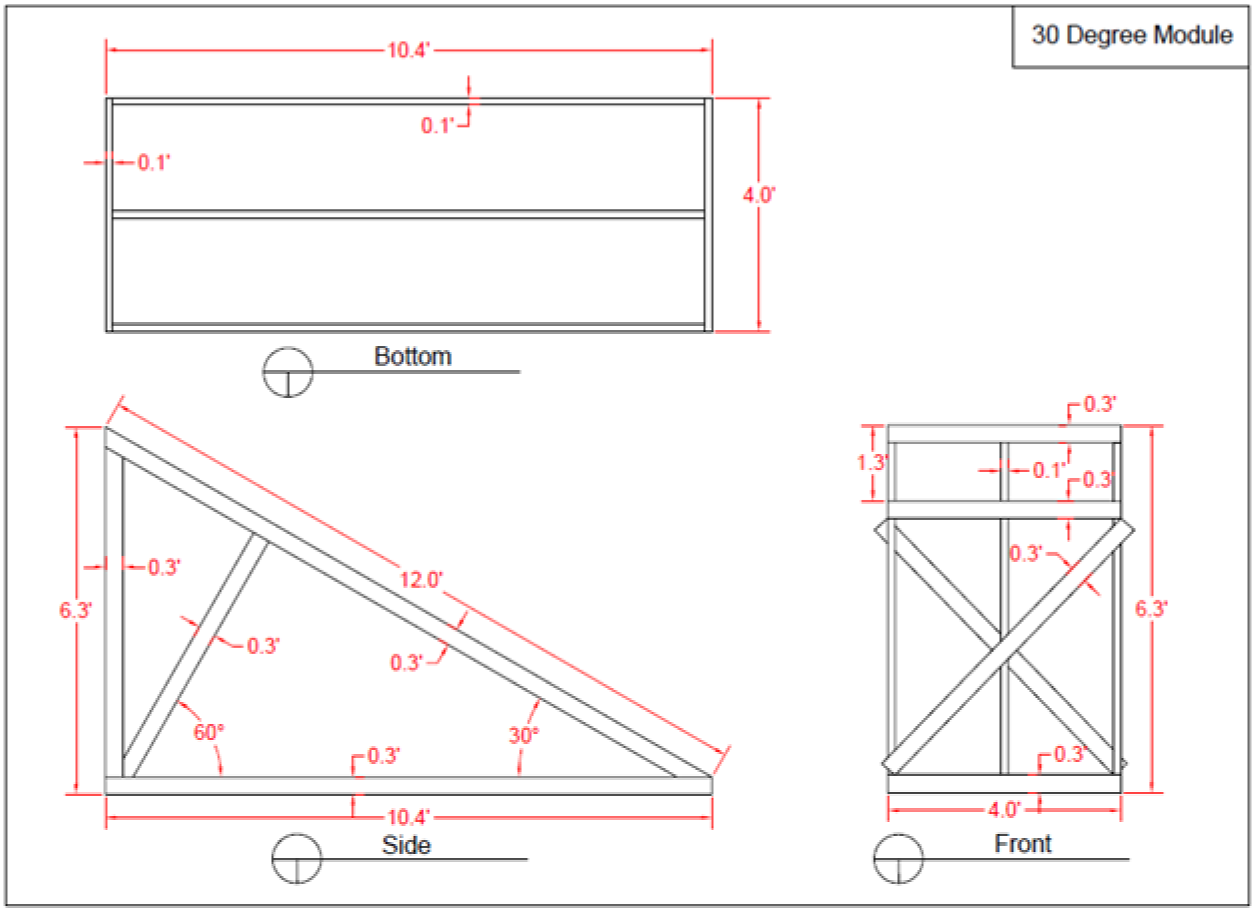

Figure 5. 30 Degree Module Design

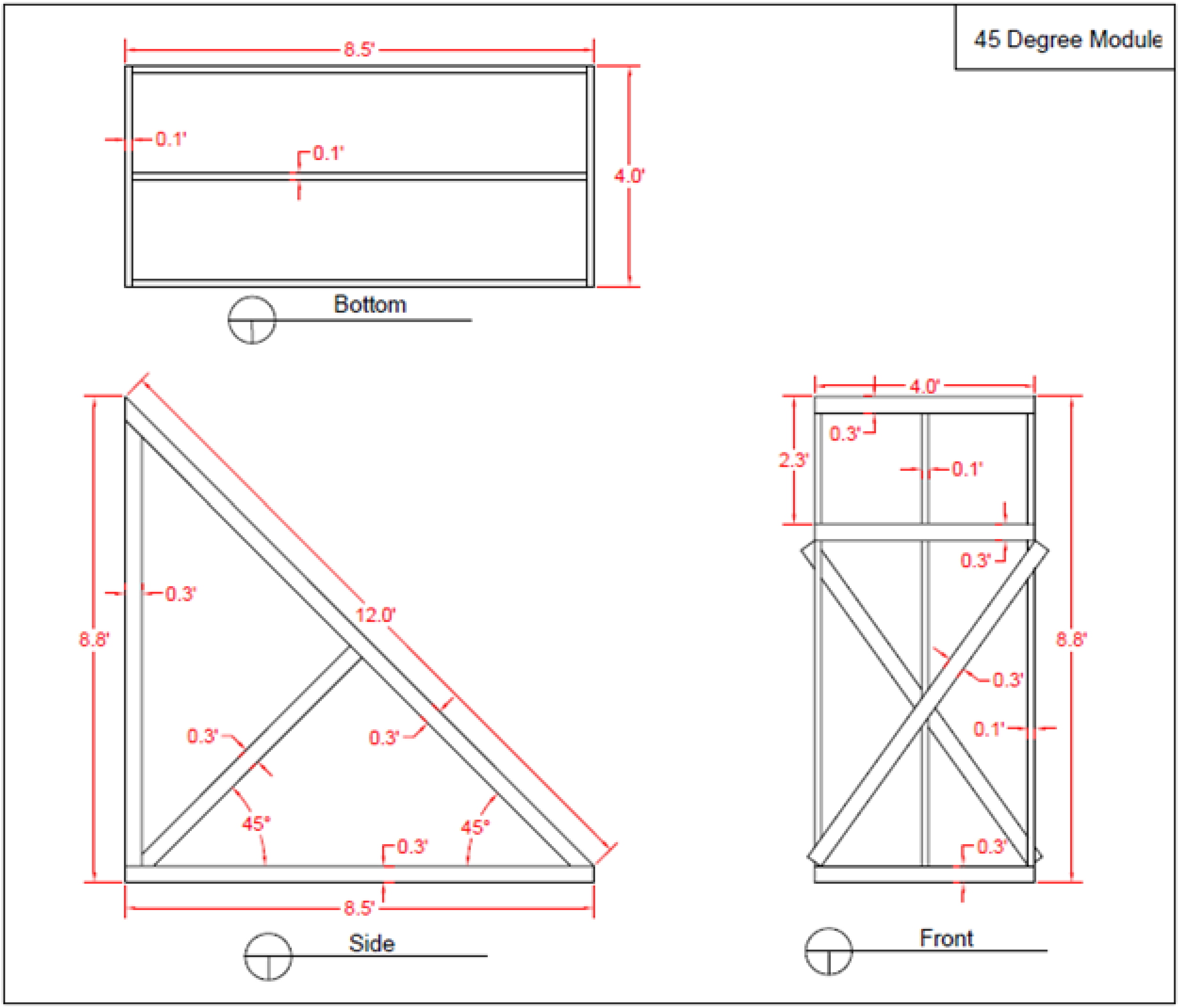

Figure 6. 45 Degree Module Design

Figures 2, 3, 4, and 5 illustrate the truss structure for the designed 2º, 15º, 30º, and 45º modules. As shown in the figures, the side sections of modules have king post truss type, which is used for simple roof trusses. King post truss consists of king post, which is a central vertical post that connects apex to the horizontal beam at the bottom, two diagonal beams that meet at the apex, one horizontal beam at the bottom, and two supporting struts. Since these modules only have one half section of a roof, it has only one king post, one diagonal beam, one beam at the bottom, and one supporting strut. Three of these side sections are spaced every 2 ft. laterally, once on each side of the module and one directly in the middle.

The live load portion of the green roof was made up of several layers (Figure 7) and include plants, a Load Support Grid® (LSG) from Cell-Tek in Crofton, MD, substrate, filter fabric, rock wool, drainage layer, and EPDM waterproofing membrane. The green roof sits on top of 5/8 in. plywood, just as it would on a residential home. The EPDM waterproofing membrane is glued to the plywood to keep water from leaking.

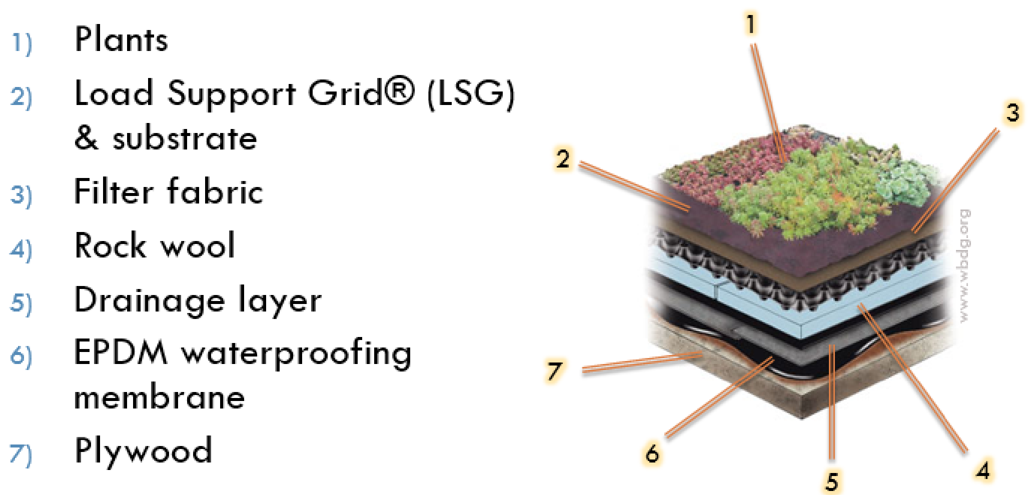

Figure 7. Green Roof Modules Layers

EPDM waterproofing membrane consists of EPDM rubber which has a chemical structure that gives it extraordinary resistance to heat, cold, and sunlight (Conservation Technology 2014). It is a lightweight material that can withstand extreme temperature fluctuations, also has high level of elasticity, and will not split or crack under normal building movement (Starry 2012). Next, there is a drainage layer, which is 0.59 in. thick, that allows water to flow to the bottom of the module and in turn prevents pooling of the water.

Above the drainage layer is a 1.18 in. layer of rock wool, which is a fiberglass material similar to insulation that retains water and slowly releases it. Rock wool, commonly known as stone wool, is a synthetic mineral product derived from the sub volcanic rock diabase (Wong 2014). Due to rock wool's exceptional water retention capability, lightweight, and durability, the team decided to use rock wool as a water reservoir. Rock wool was expected delay the peak flow rate of runoff and will act as a supplementary substrate layer, where roots can hold onto and grow. The filter fabric was then placed between the rock wool and the substrate, preventing fine particles of substrate from passing through to drainage layer. It was expected to act as a capillary layer to spread water out to the plant roots. The Load Support Grid (LSG) retained the substrate and kept it from sliding to the bottom of the platform. Each cell of LSG was filled with two in. of substrate and had at least one plant in it. The LSG was cut about 2 in. higher than the substrate.

A variety of Sedum plants traditionally successful on flat green roofs were used. These plants included S*edum album, S. kamschaticum, S. sexangular, S. reflexum, S. hybridum, and S. spurium*. Sedum is the preferred plant for green roofs because they are tough, durable plants that are resistant to heat and tolerant to droughts. Leaves grow close together and are dense, providing decent coverage (Rowe et al. 2012). Some of these plants provide foliage during the winter months. The plants used are specific to the Mid-Atlantic region. The team decided to use a mix of plants, because it was found through previous research that different plants colonize on different parts of the roof at different times (Rowe et al. 2012). Some plants will completely colonize a roof during different seasons, because they have differing peak growing times. It is important to ensure that green roofs always have plant coverage in order to keep them aesthetically pleasing and to maintain the stormwater mitigation performance of the roof. Since the different plant species were placed randomly around the modules, this created a meadow effect. The plants spread out in no particular order which simulated a more natural environment.

Before planting, the team made sure to wash off the roots to improve root/substrate contact. The team began planting the Sedum in October 2013 and observed the plant growth through November 2014. Plants in the control module performed the best, probably due to greater water availability. *Sedum kamschaticum* was the most successful in establishing in all modules.

Several of the performance measure methods contained factors that were outside of the team's control. Firstly, the nature of rainfall was unpredictable. The intensity, duration, and direction of rainfall changed from one storm to the next. This caused difficulty when assessing the effectiveness of the green roof system's ability to mitigate stormwater runoff. Many assumptions were made due to the limited ability to assess the rain's behavior. In order to evaluate the amount of water which reached the roof, the team assumed that rain fell straight down and determined the projected area of the modules accordingly. This assumption allowed the team to determine the percentage of water which flowed through the system and out of the gutter, but the precision of the measurement is limited due to the assumption regarding the rainfall. Rainfall was measured at the greenhouse weather station every ten minutes by a Decagon ECRN-100 rainfall gauge. The length of time that data was collected was also limited as the data collection time period lasted only six months, from June 2014 – November 2014. This short of a time period creates problems when analyzing runoff data because the rain events during this six month period (summer and fall) may not have been representative of the weather that the system would experience throughout the year. The instruments used for measuring runoff also limited the accuracy of the runoff data collected. The team used ECRN-100 high resolution rain gauges on each module. These sensors utilize a double-spoon tipping bucket which have a resolution of 0.2 mm. This can limit the resolution of the runoff measurements and cause possible error. If the rainfall runoff volume was too large, the gauge's capacity was overwhelmed and would not accurately measure the volume.. The accuracy is also limited by the ability of the gutter system to properly direct all of the runoff from the module into the rain gauge. It is possible that heavy flows could have not fallen directly into the gauge. However, the gauges were useful in determining when the runoff started and stopped.

Performance Measures

The primary performance measures for the roof modules were volumetric water content and runoff volume. Volumetric moisture content of the roofs provided a better understanding of how effectively the modules retained water after precipitation. The moisture content data was collected by 5TM temperature and moisture probes (Decagon Devices, Pullman, WA) inserted into the rock wool layer in each of the modules. Four probes were placed in each module in the lateral center of the module. The probe positions along the slope are described in Table 2 and Figure 8.

Table 2. Probe location in the rock wool layer: bottom of the slope (sheet 1) to the top of the slope (sheet 6)

Probe	Location in Rock Wool
1	Top of Sheet 1
2	Bottom of Sheet 3
3	Bottom of Sheet 5
4	Top of Sheet 6

Figure 8. Rock Wool Diagram

SO GREEN's project was the first green roof research project to use volumetric water content probes (VWC is the percent of water in the substrate) on a sloped green roof. The data collected from the probes was used to determine:

1. How rainfall changed the water content in the green roofs modules
2. How long after a rain event the modules retained water
3. How the water content before a storm affected the retention capabilities of the modules

Runoff measurements were taken using a rain gauge at the base of each module's gutter. The rain gauges had a tipping volume of 0.2 mL, meaning that anytime the runoff leaving the gutter passed 0.2 mL, the rain gauge tipped and the time was recorded. This allowed the researchers to see how the storm intensity changed with time, and how that intensity affected the water retention on the modules. The runoff volume was also measured as a total quantity by a flow meter (Grate Plains Industries, Wichita, KS). The complete water flow path on each module was through the module, into the gutter, through the rain gauge, into a collection barrel, where it was pumped through a flow meter into another collection barrel. The total volume of water to pass through the flow meter was then recorded about 24 hours after each rain event. This was enough time for the water to drain through the roofs. By comparing the recorded number to the total precipitation collected by the UMD Greenhouse weather station, the team could see how much water was retained and transpired back into the air versus how much ran off the modules using the water balance equation below.

$$Precipation = Runoff + Evapotranspiration + \Delta Storage$$

Other important performance metrics were based on storm intensity and storm size. The metrics are defined in tables 3 and 4. Storm intensity and size impact how easily green roofs can absorb and hold stormwater. The larger the storm size or intensity, the less able a green roof is to mitigate stormwater runoff. In the next section, a discussion of how these metrics impact runoff delay, VWC, and percentage of stormwater retained in green roof performance is explained. Divisions based on (Barton 2015).

Table 3. Storm Intensity

Rate (r) of Rainfall (mm/hour)	Intensity
r < 7.62	Low
12.7 > r > 7.62	Mid
r >12.7	High

Table 4. Storm Size

Precipitation (mm)	Size
< 12.5	Small
12.5 - 62.5	Medium

Module Weight

A critical aspect of implementing a green roof retrofit without structurally reinforcing an existing home is making sure the retrofit remains lightweight. Since only 2 in. of media are being utilized in the retrofit roof it should be no more than 10 psf while dehydrated. The goal of 10 psf was selected based on Green Roof Technology definition of extensive green roofs. Green Roof Technology declares that extensive green roofs have a range of 3 - 6 in. of substrate, and range in weight from 15 - 25 psf. That roughly means that for every additional inch of substrate used there is an added weight of 5 psf. By eliminating an inch of substrate, allowing 5 psf to be subtracted, the projected goal weight for creating a roof with 2 in. of substrate was set as 10 psf. The state of Maryland supplies the following table, shown in table 5, to describe snow loads that roofs must be designed to hold.

Table 5. Maryland Snow Loads

Local enforcement agencies	Ground Snow loads (Pg)
Garrett and Allegany	55 psf
Washington, Frederick and Carroll	40 psf
Baltimore, Cecil, Harford, Howard, and Prince George's	35 psf
Montgomery	30 psf
All other counties	25 psf

These weights are live loads and are in addition to the dead load of a roof. A typical asphalt shingle roof with ⅝ in. plywood weighs 5-15 psf (The Engineering ToolBox 2015). Designing a roof under 10 psf is the success criterion for the weight of the retrofit.

In order to determine the exact weight of the retrofit designed, a 1 ft. x 1 ft. square was assembled of the green roof system. These materials included the EPDM waterproofing membrane, the drainage layer, the rock wool, the filter fabric, the substrate, and the slope retention grid. The substrate was measured by multiplying 2 in. by 1 ft^2 to determine the necessary volume. A large bin was weighed on a scale and the tare weight was measured to be

619.3 g. All green roof layers were then placed underneath a water source until saturated. The layers were then placed in the bin and the saturated weight was measured. A week later, after the moisture had evaporated and the layers were dry, a measurement was taken for the dry weight.

Module Weight – Analysis

In the analysis of the 1 ft^2 square's weight, the team intended to see if the module design reached the goal of weighing less than 10 psf, dry weight. As explained previously, a normal residential roof bears between 5 and 15 psf of dead load, which means that the green roof retrofit would have to weigh close to this in order to be sustained successfully on an existing home. In this analysis, the team also intended to see if the module design reached the goal of weighing less than 25 psf while saturated, because residential roofs can hold from 15 to 45 psf of live load in addition to the 10 psf of dead load.

The team found the final dry weight of the 1 ft^2 module of the roof component system to be 4,450 grams or approximately 9.81 psf. Under saturated conditions, the weight of the modules increased to 7,295 grams or approximately 16.08 psf. Both these values fall below the dry and saturated weight limits of 10 and 25 psf. In future studies, more soil media can be added to the roof systems to improve plant growth without compromising the structural integrity of the green roof systems or the residential roofs.

Live loads include a myriad of different factors besides rain, such as snow, wind, and seismic activity. The team did not have the means to test the loads on the 1 ft^2 module from these types of events due to project limitations, but there are equations available to calculate the required strength of the module given a hypothetical load, which include snow and wind.

VWC - Storm Size

Volumetric water content measurements show that slope highly affected this performance measure. The sensor at the bottom of each module showed that, compared to the flat roof, the sloped roofs retained far less water. There was no apparent difference amongst sloped roof modules. The average volumetric water content during medium events shows this difference most prominently, although it is present in the small events also. Figures 9-28 show the average volumetric water content during small and medium rain events based on sensor locations. Note that the graphs for port four (sensor at the top of each module) show no apparent difference. The expected trend that locations higher on the roof would be drier than lower locations is seen across all modules.

Small Events

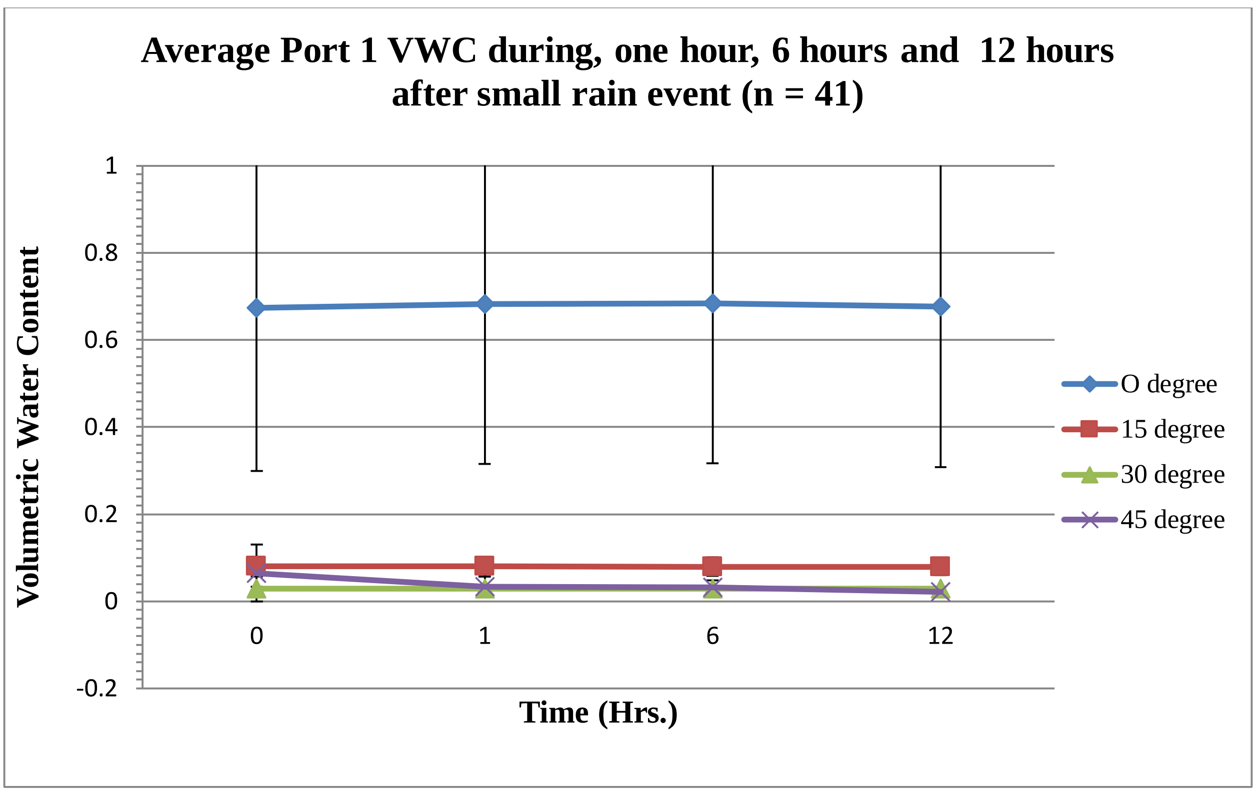

Figure 9. Average Port 1 VWC After Small Rain Events (error bars represent standard deviation (SD) among rain events)

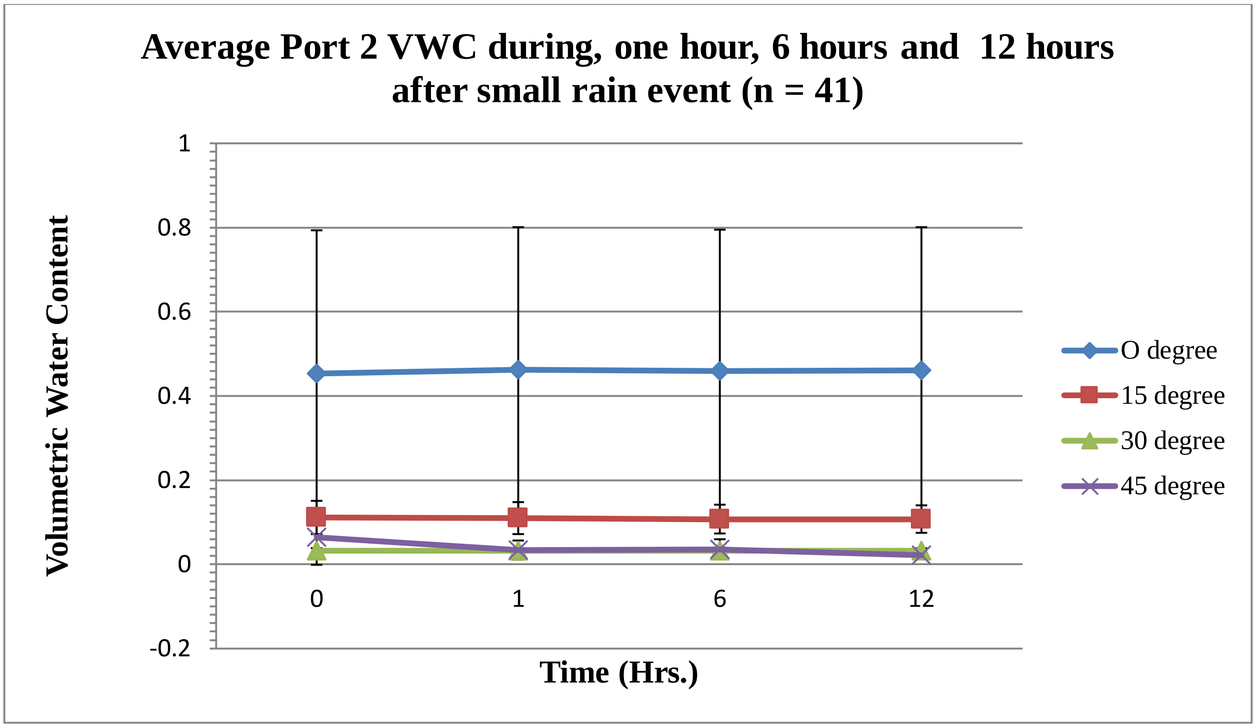

Figure 10. Average Port 2 VWC After Small Rain Events (error bars represent SD among rain events)

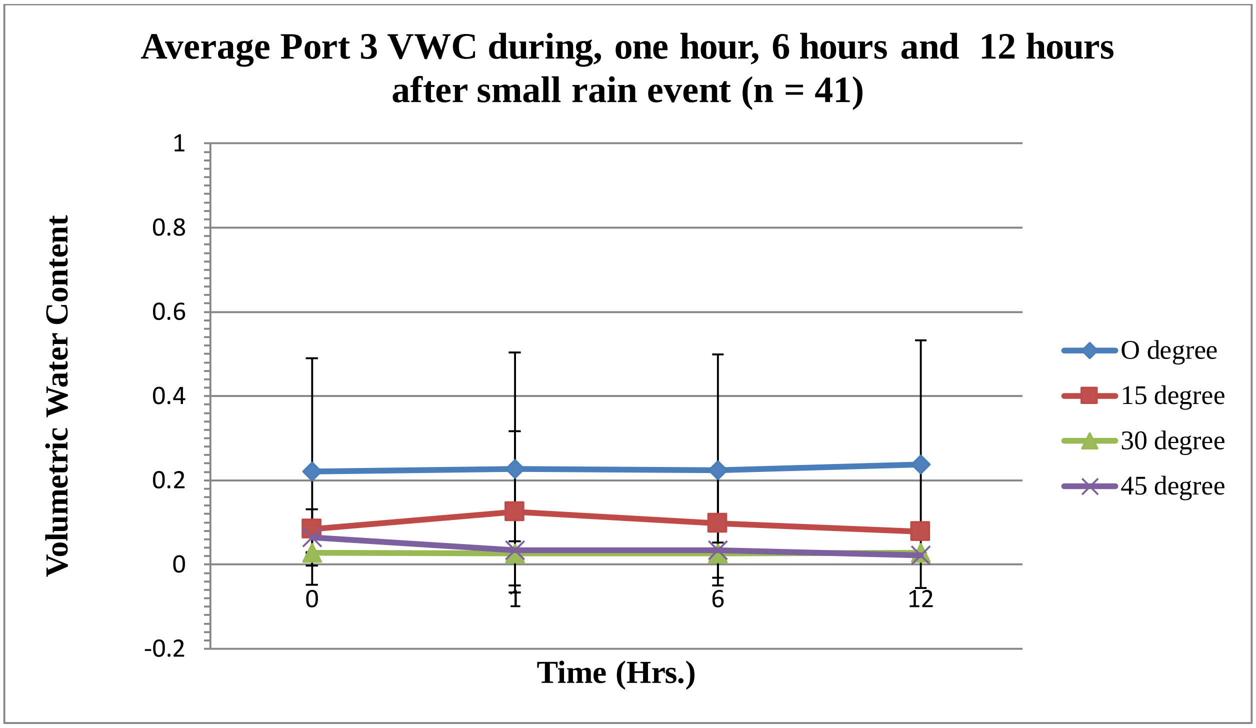

Figure 11. Average Port 3 VWC After Small Rain Events (error bars represent SD among rain events)

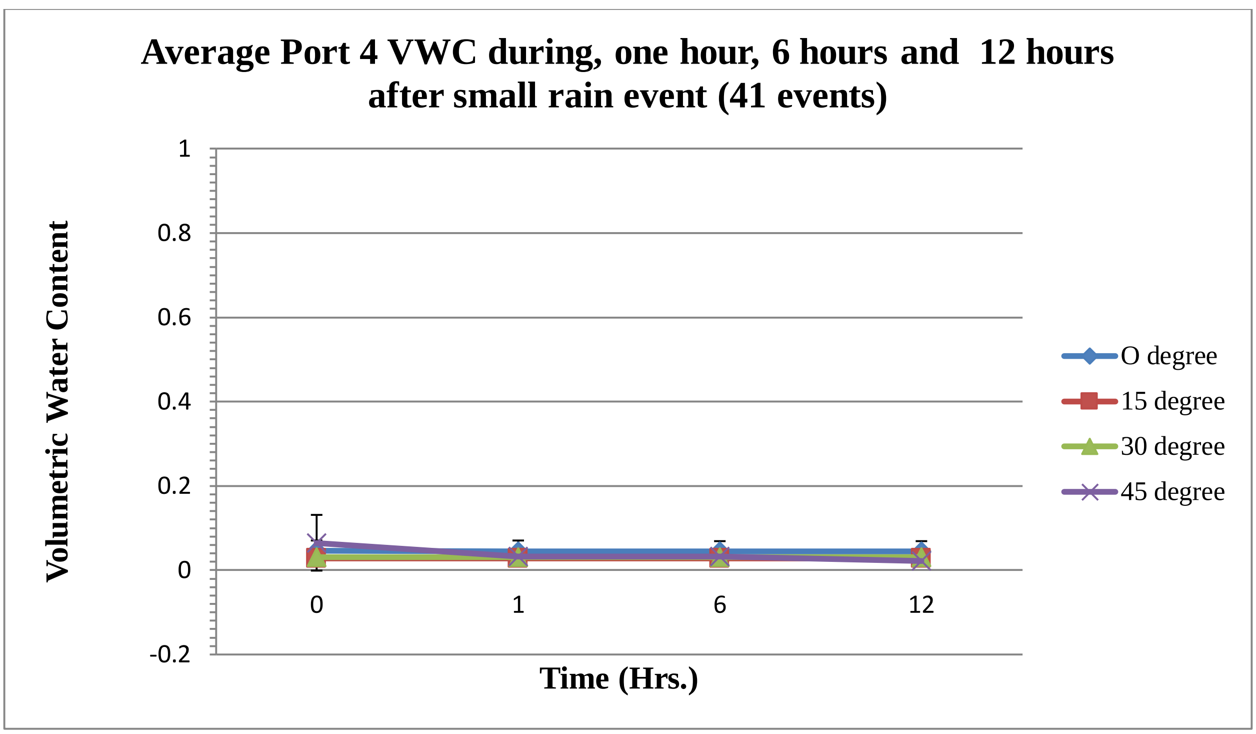

Figure 12. Average Port 4 VWC After Small Rain Events (error bars represent SD among rain events)

Medium Events

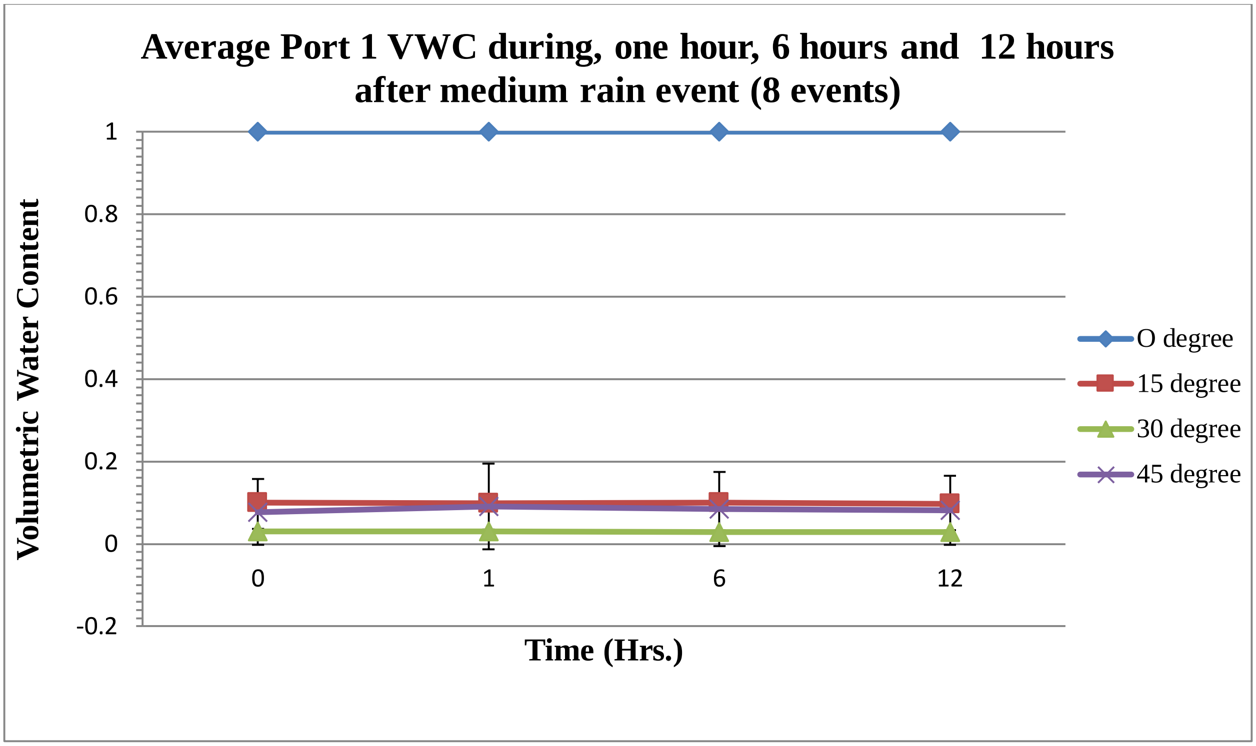

Figure 13. Average Port 1 VWC After Medium Rain Events (error bars represent SD among rain events)

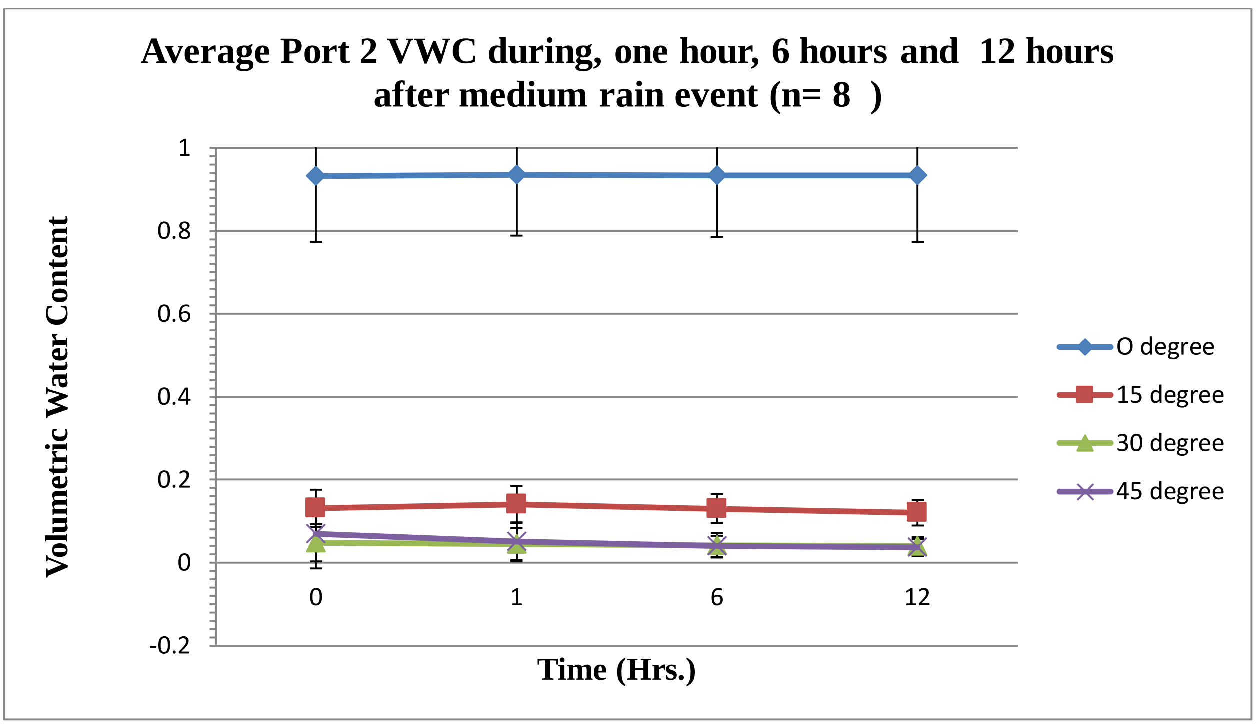

Figure 14. Average Port 2 VWC After Medium Rain Events (error bars represent SD among rain events)

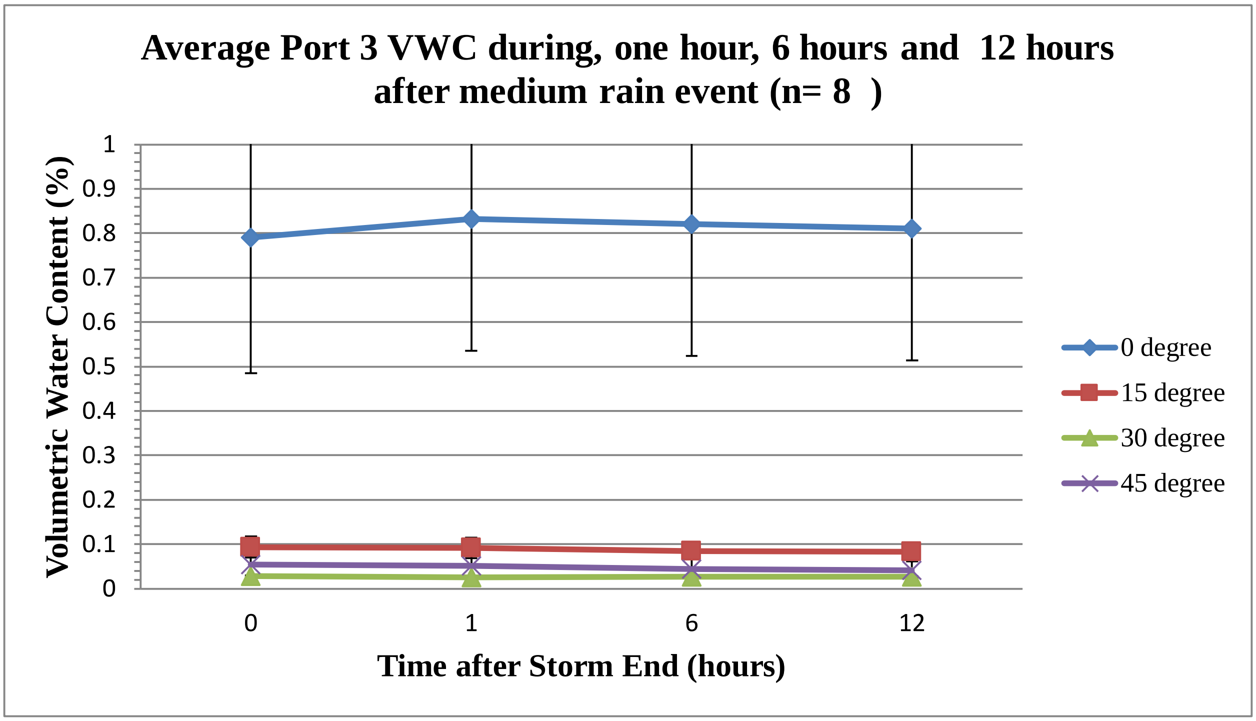

Figure 15. Average Port 3 VWC After Medium Rain Events (error bars represent SD among rain events)

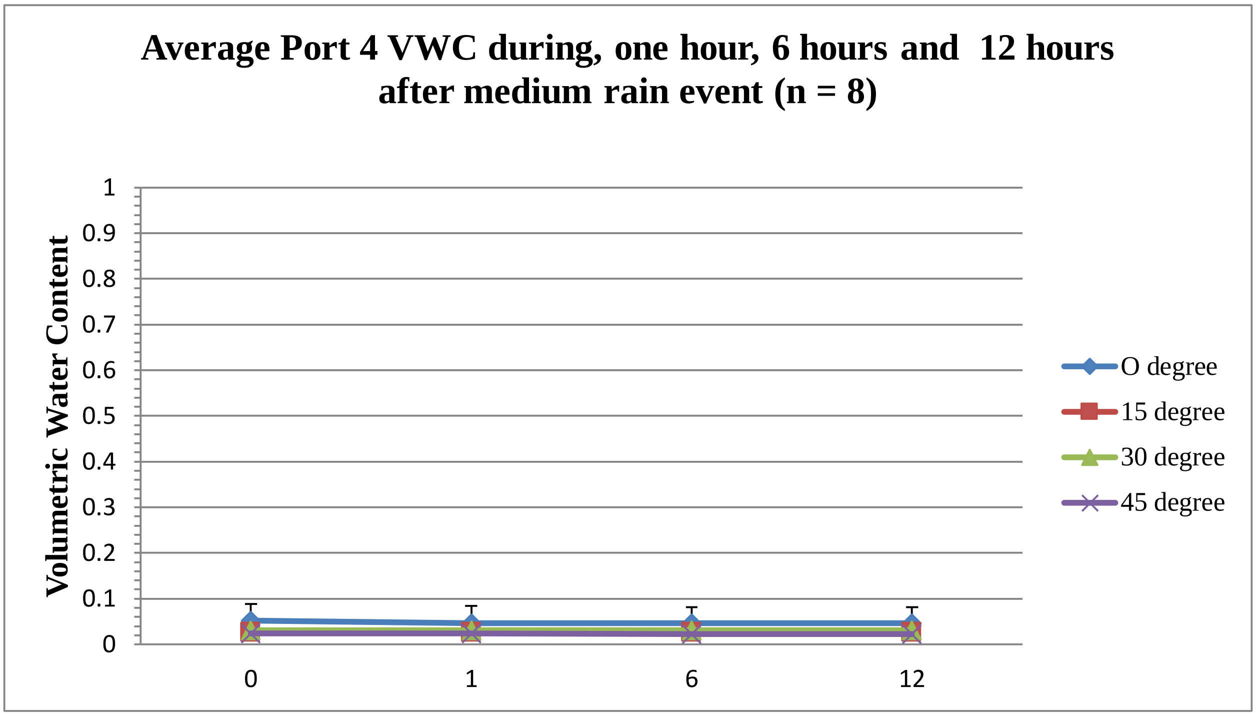

Figure 16. Average Port 4 VWC After Medium Rain Events (error bars represent SD among rain events)

VWC - Storm Intensity

The team also looked at volumetric water content of each module during different storm intensities. Within the data collected, thirty-eight events had low intensity, eight events had medium intensity, and seven events had high intensity. The effects of storm intensity on volumetric water content are not well known. In this study, volumetric water content was different between the control and sloped roofs for all levels of intensity at port locations one and two. There was also an apparent difference between control and sloped roofs for port three during high intensity events.

Low Intensity Rain Events

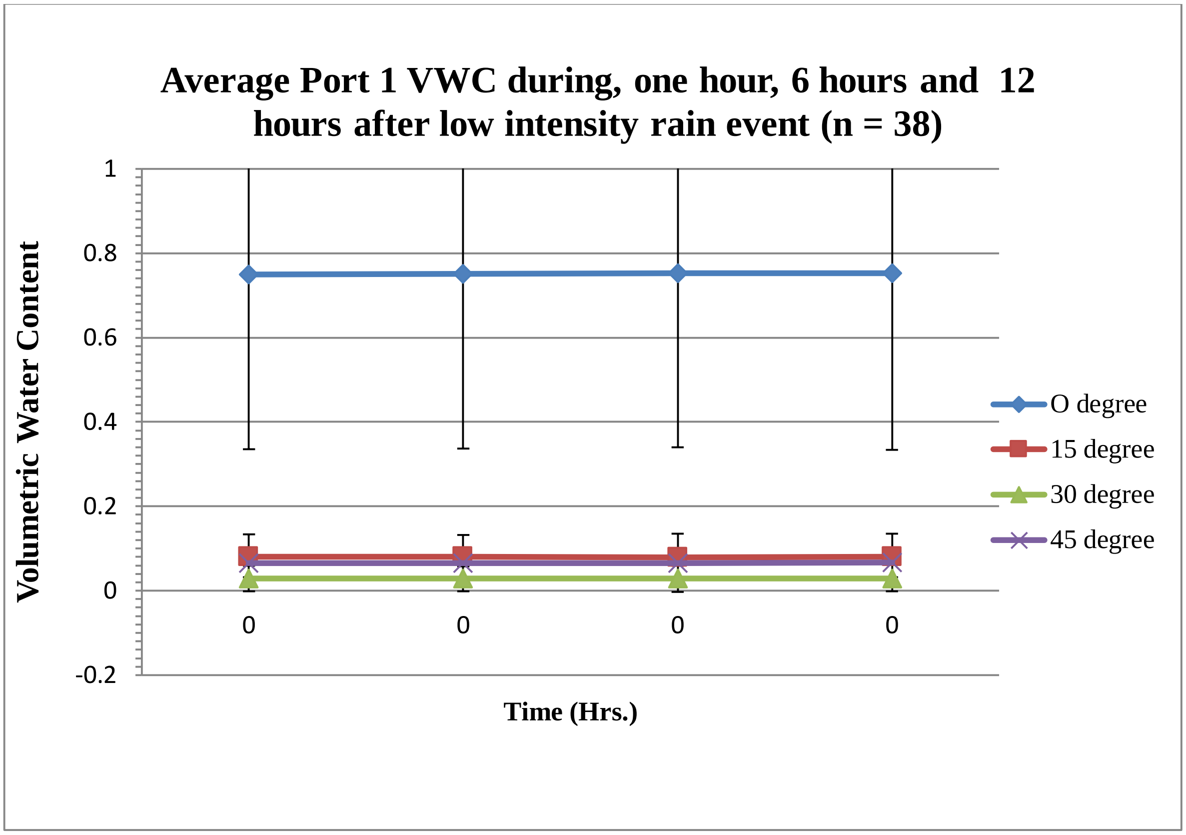

Figure 17. Average Port 1 VWC After Low Intensity Rain Events (error bars represent SD among rain events)

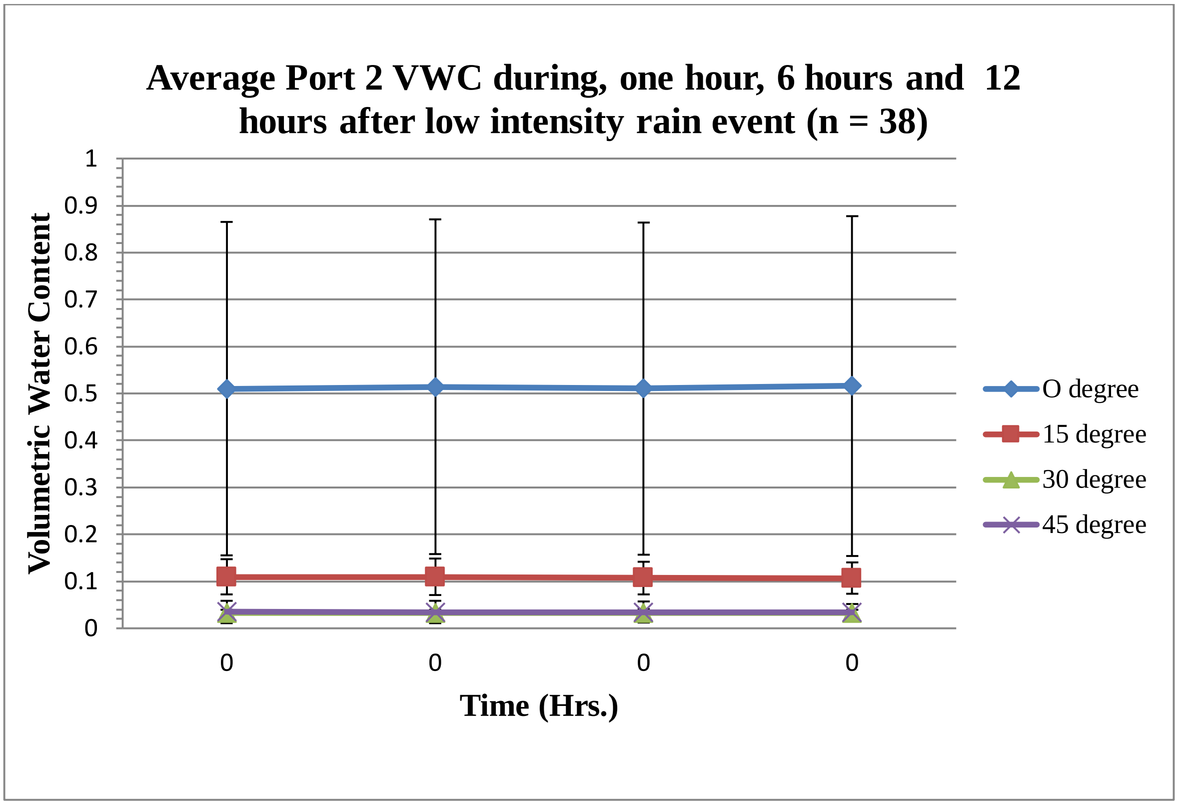

Figure 18. Average Port 1 VWC After Low Intensity Rain Events (error bars represent SD among rain events)

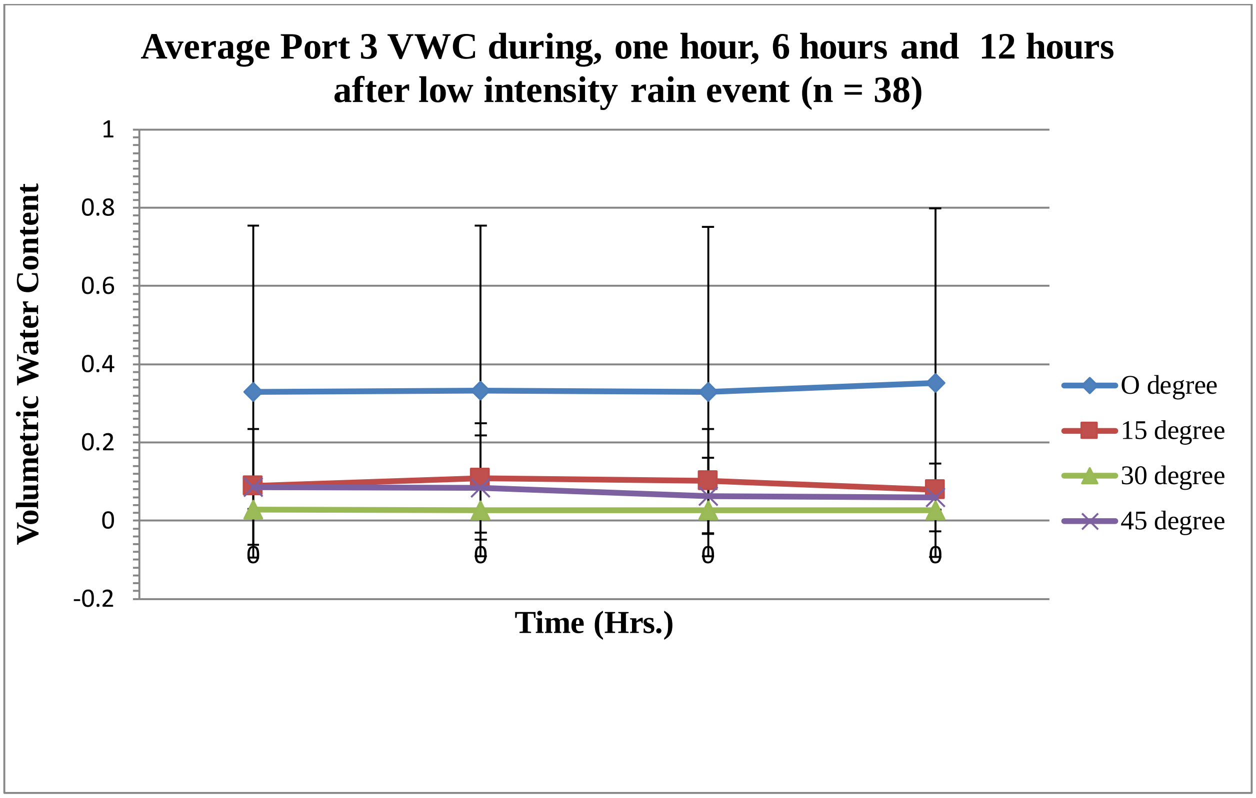

Figure 19. Average Port 3 VWC After Low Intensity Rain Events (error bars represent SD among rain events)

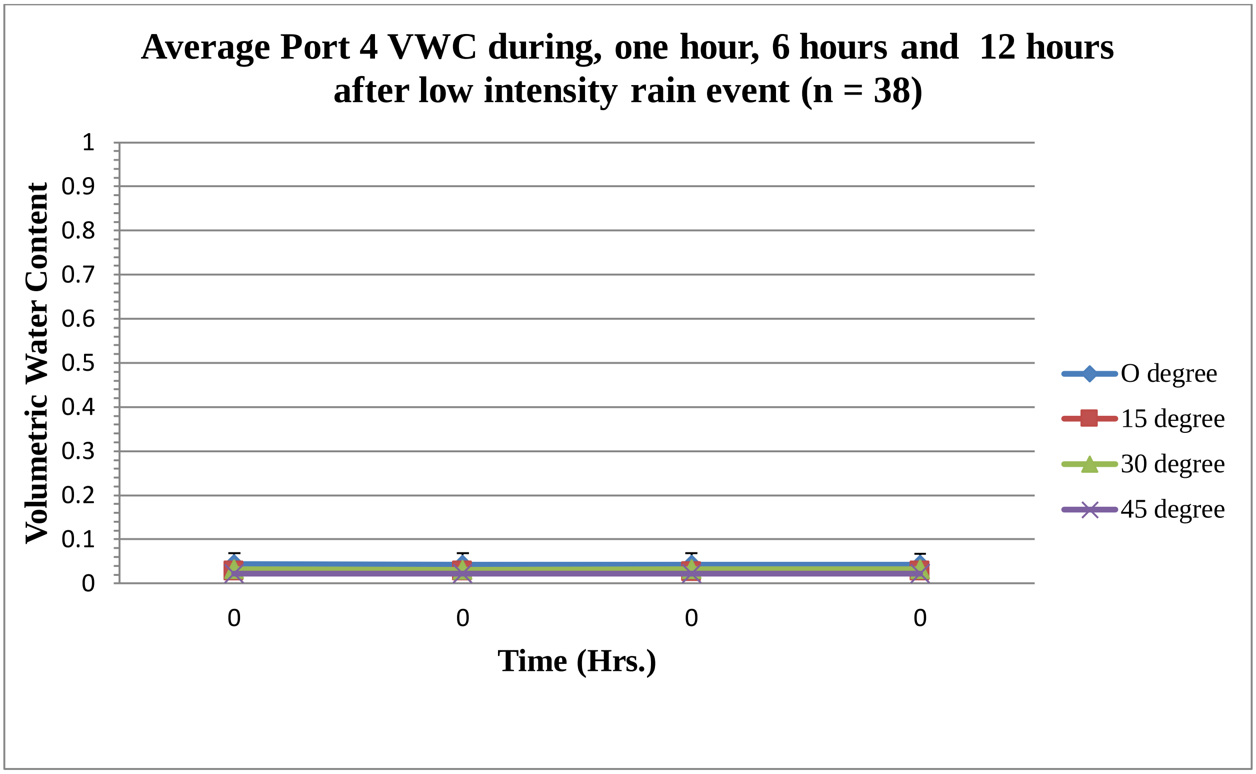

Figure 20. Average Port 4 VWC After Low Intensity Rain Events (error bars represent SD among rain events)

Medium Intensity Rain Events

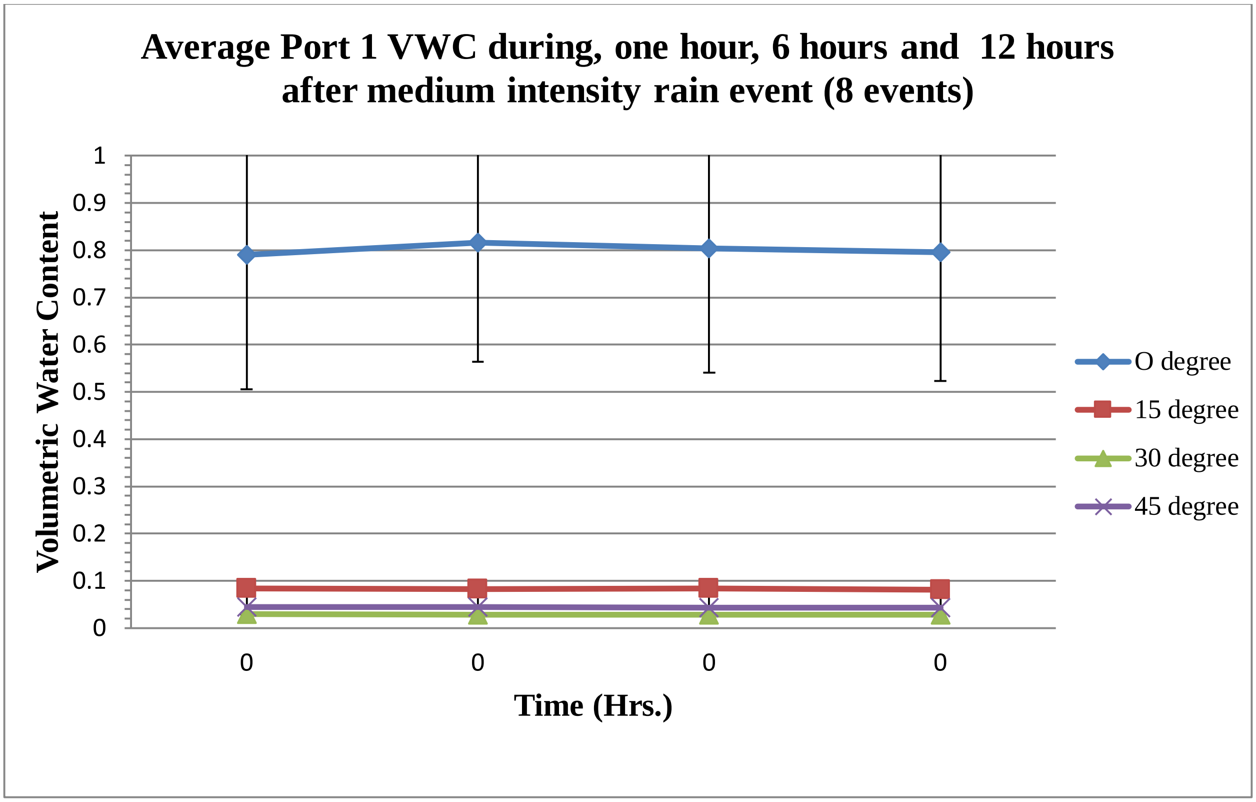

Figure 21. Average Port 1 VWC After Medium Intensity Rain Events (error bars represent SD among rain events)

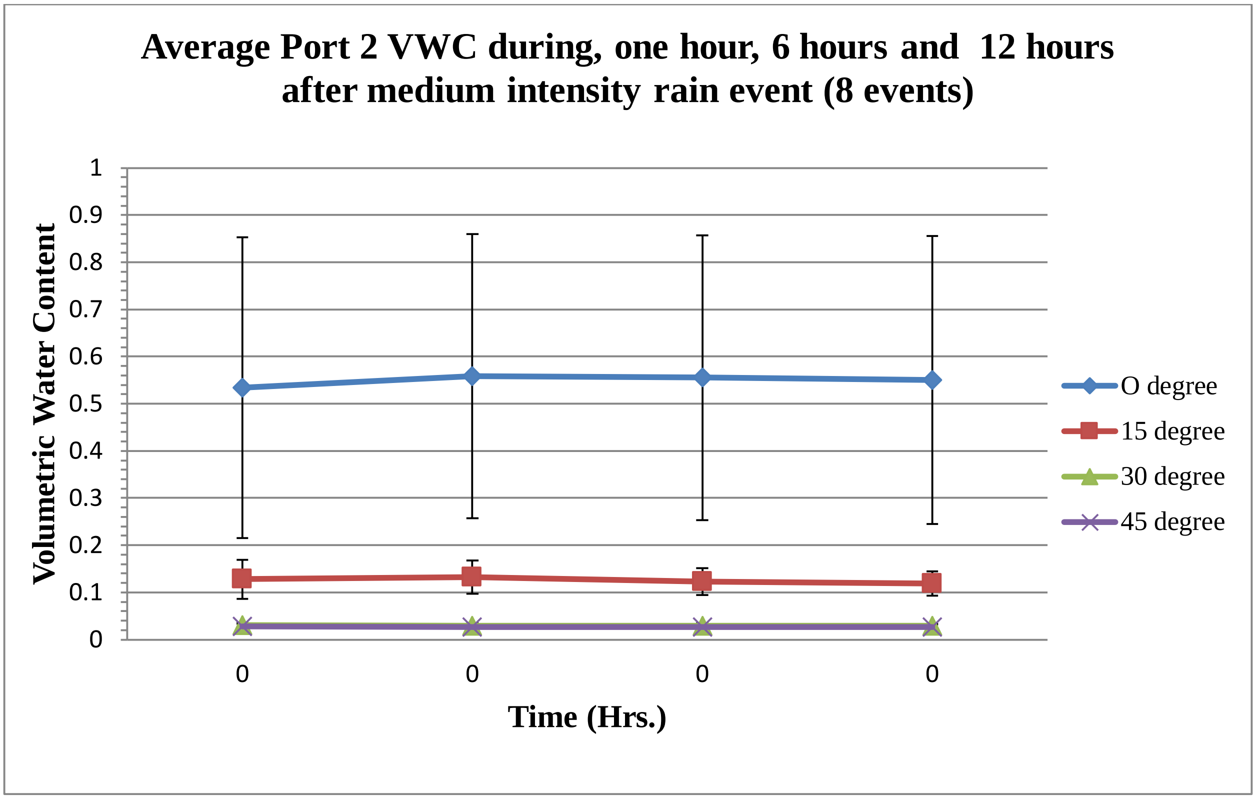

Figure 22. Average Port 2 VWC After Medium Intensity Rain Events (error bars represent SD among rain events)

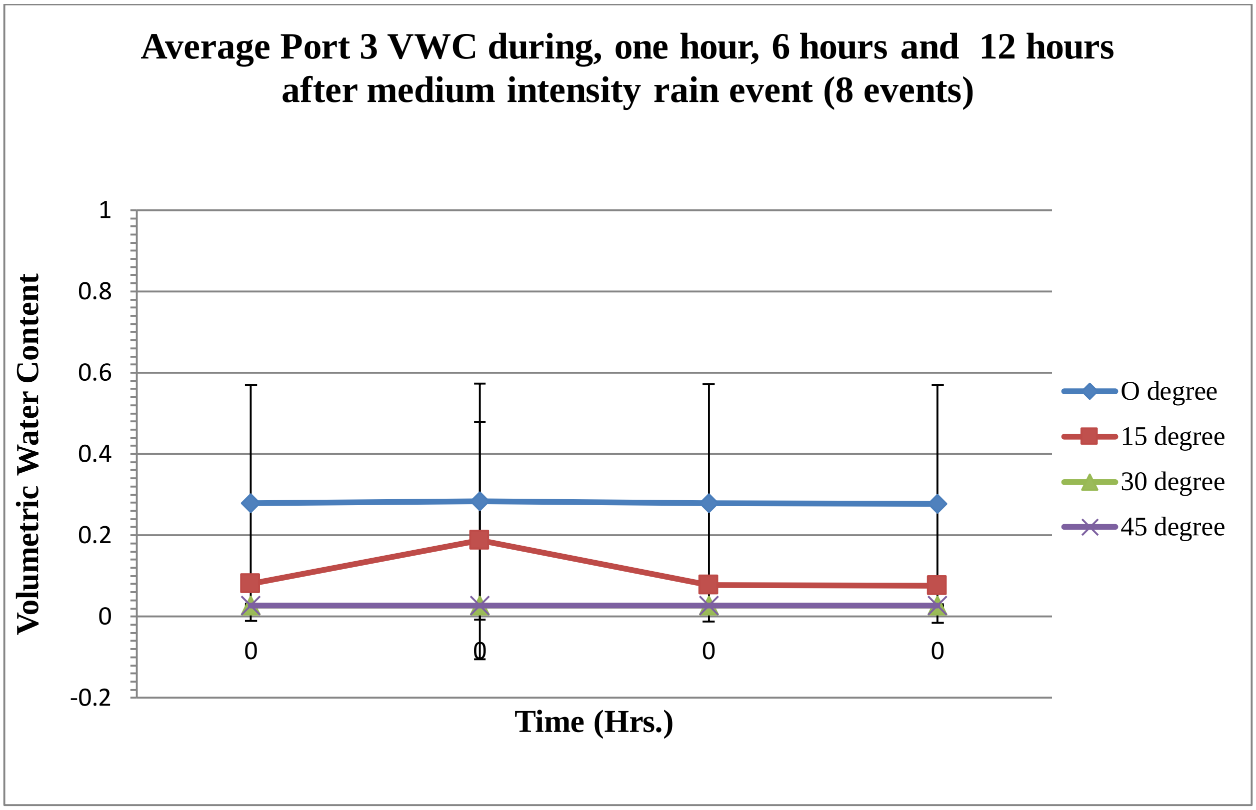

Figure 23. Average Port 3 VWC After Medium Intensity Rain Events (error bars represent SD among rain events)

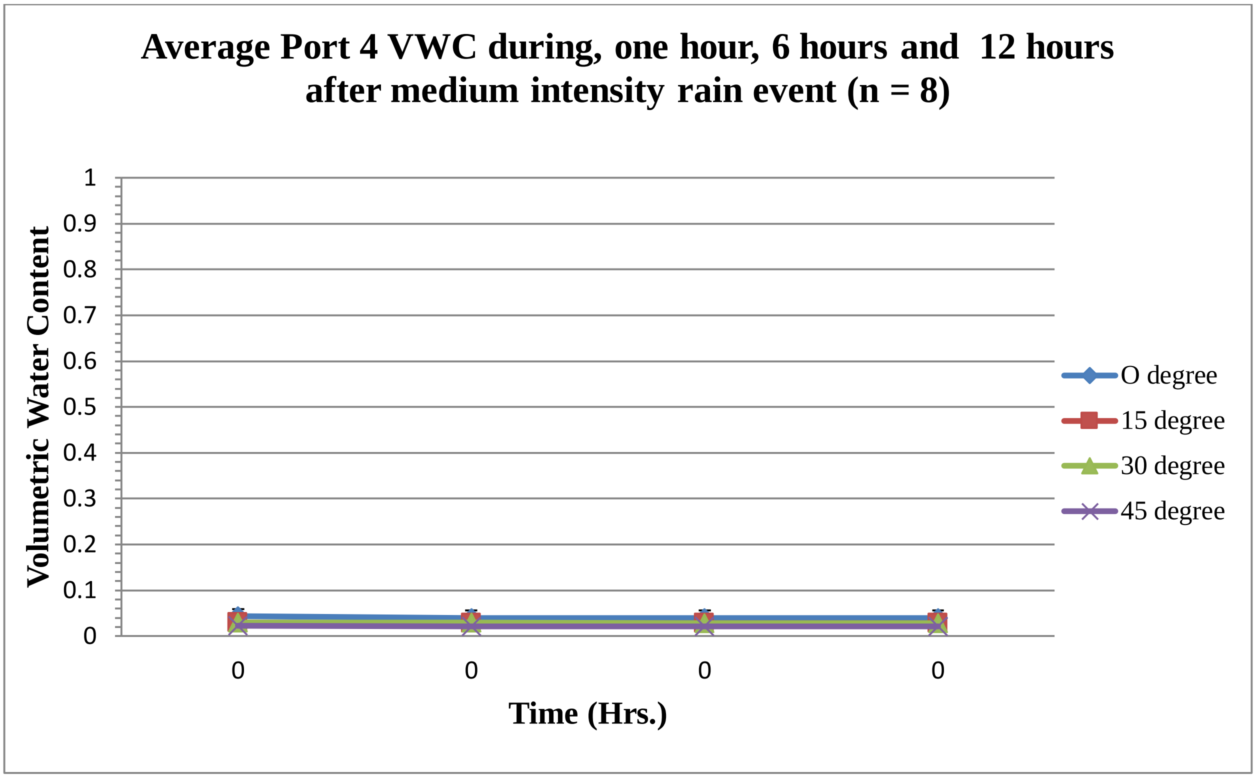

Figure 24. Average Port 4 VWC After Medium Intensity Rain Events (error bars represent SD among rain events)

High Intensity Rain Events

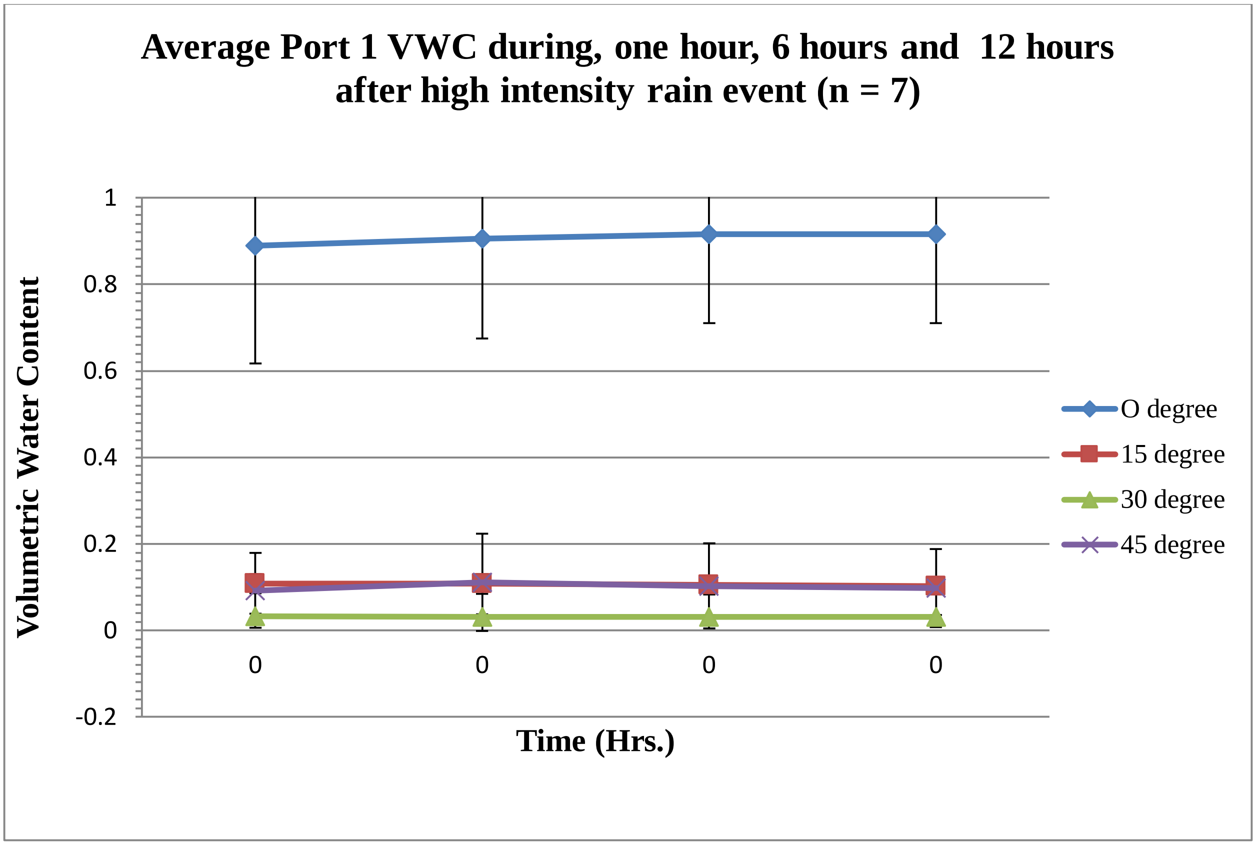

Figure 25. Average Port 1 VWC After High Intensity Rain Events (error bars represent SD among rain events)

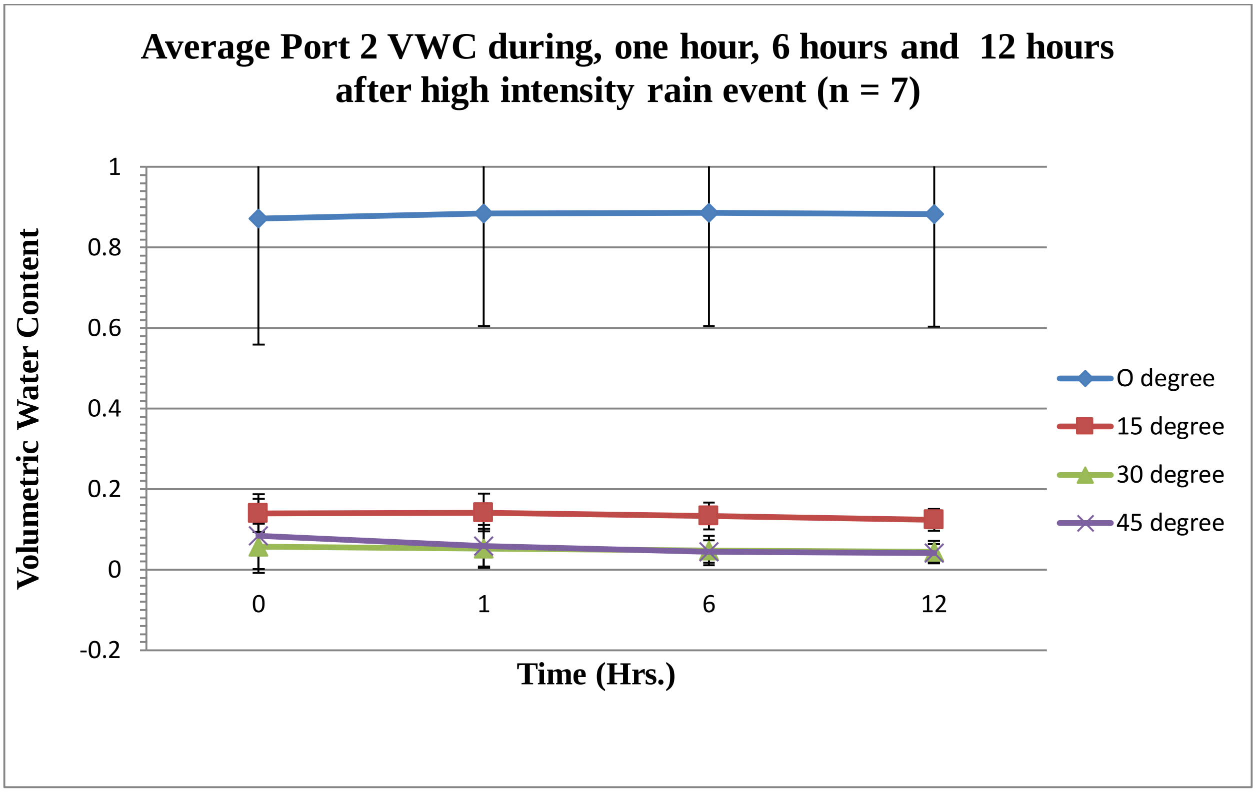

Figure 26. Average Port 2 VWC After High Intensity Rain Events (error bars represent SD among rain events)

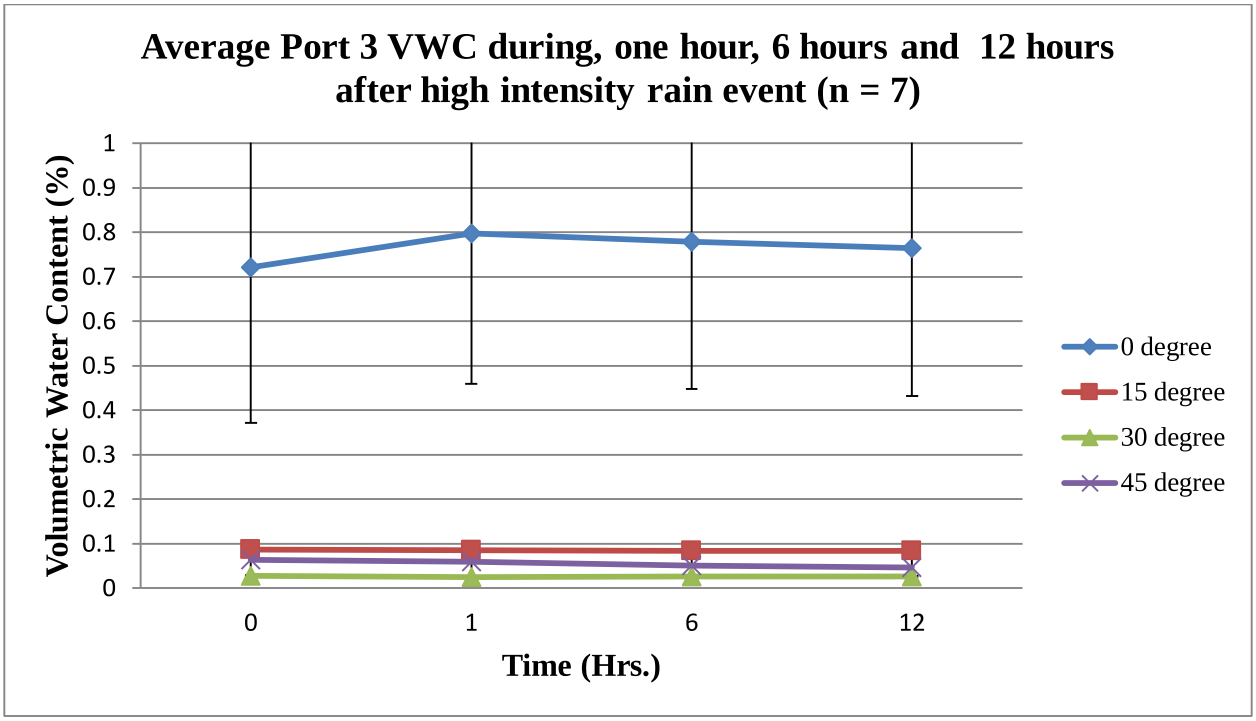

Figure 27. Average Port 3 VWC After High Intensity Rain Events (error bars represent SD among rain events)

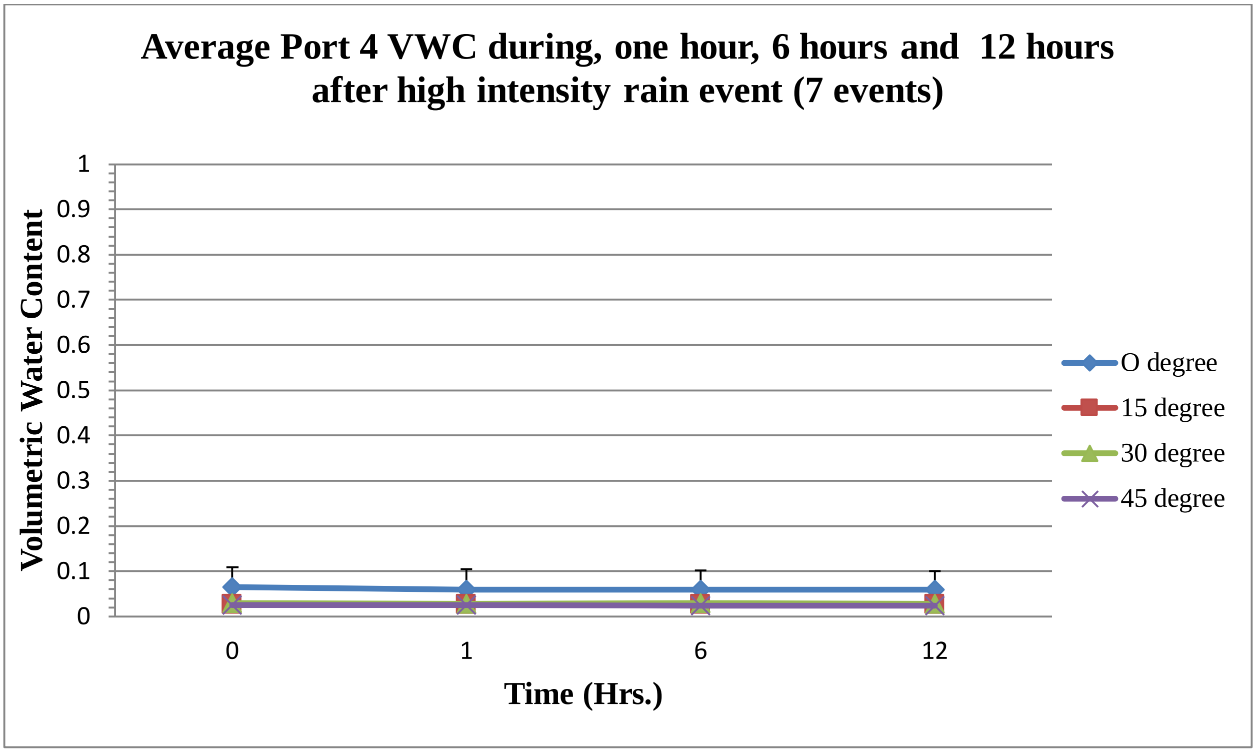

Figure 28. Average Port 4 VWC After High Intensity Rain Events (error bars represent SD among rain events)

Runoff

In order to analyze the runoff of the roof modules, runoff measurements were taken 24 hours after the completion of the rain event from the flow meters. Each time that a reading was taken, the meters were set to zero so that the total accumulation of the following rain event could be found. The team wanted to look at the ability of the roof to capture and retain rainfall. In order to account for the rainfall on each roof, the team took into account the slope of the roof and assumed the rain came straight down. This leaves some room for error as rain does not generally fall straight down but the team did not make such observations during data collection. The team proceeded to make a ratio of total runoff to total rainfall that fell on the roof. This gave a general idea of the performance of the roof in terms of water retention.

The team collected rainfall data for every storm event over a 6 month period using the weather station at the greenhouse at the University of Maryland. These numbers were then compared with the total runoff collected after each storm event. The ratio of runoff to rainfall for each module after every storm event was calculated and then averaged. These values are presented below in Table 6. While it was difficult to observe a clear correlation between slope and the volume of water held in by the module, all four modules were able to hold a portion of the rainfall.

Table 6 – Average Stormwater Retained for Each Module

Slope	Control	15º	30º	45º
Stormwater Retention (%)	62.1	53.1	52.7	43.9

Runoff Delay

Determining the length of time from the start of a rain event to when a green roof starts leaching water is an integral metric for evaluating design effectiveness. Runoff delay was calculated by determining the time between the first recorded precipitation and the first recorded runoff leached from each platform. First recorded precipitation was the time of the first five-minute increment during which rainfall was recorded by the UMD weather station. First recorded runoff was the time of the first ten-minute increment in a string of non-zero increments during which runoff was recorded from each green roof's runoff sensor.

An interesting phenomenon was observed when analyzing data. It was noted that the sloped modules would have no runoff during small rain events, while the control module would have substantial runoff. This correlates to the control's much greater VWC over the course of this study, causing it to shed water more easily during rain events. However, this means the sloped modules were less saturated and drained more fully between rain events, indicated by their lower VWC. When rain events occurred just beyond 12 hours from each other, the modules were more susceptible to runoff. This was the case regardless of storm size. When there was runoff, the sloped modules typically had shorter times until runoff was recorded compared to the control module. The flat roof held water longer before leaching, but the flat roofs remained well drained and more capable of absorbing lighter, smaller rain events. Averages can be seen in Tables 7 and 8.

In order to analyze the runoff delay benefit of each green roof module, the storm events were separated by storm size as defined by the total amount of rainfall over the entire duration. For each rain event, the start time for rainfall, as logged by the weather station at the University of Maryland greenhouse, was recorded. The start time for runoff from each module was then recorded. The difference between these values showed the amount of time for water to filter through the system and runoff of the module. Certain rain events had no runoff which would be quantified as an infinite time before runoff; therefore in order to determine the average leach time for each module, the values between 0 and positive infinity needed to be scaled down. The team took each value for runoff and scaled them using the following inverse relationship.

$$X = \frac{1}{e^{minutes}}$$

This relationship scales the values to represent positive infinity minutes as X = 0 and zero minutes as X = 1, where X is the inverse of the inverse natural logarithm of runoff delay in minutes. These X values were then averaged together for each module. Once the average values were obtained, the natural logarithm of the inverse of X was used to calculate the average time in minutes for each module to leach the stormwater.

$$minutes = \ln\frac{1}{X}$$

These values for each module were then compared to determine if there was any sign of difference between the different module slopes and the varying storm sizes. The same method was then used to compare the runoff delay for each module with the storm intensity, as defined by the amount of rain per unit.

Table 7. Delay (min) of Runoff for Each Platform vs. Storm Intensity

	Control	15º	30º	45º
Small	158.36	149.50	173.53	118.51
Medium	47.47	82.15	61.10	43.84

Table 7. – Delay (min) of Runoff for Each Platform vs. Storm Intensity

	Control	15º	30º	45º
Low	182.21	205.68	211.75	217.24
Mid	183.11	103.17	145.88	102.32
High	7.62	36.99	22.77	22.01

In Table 7, it is seen that the difference between the runoff delay for small and medium storms is about a factor of two; however, delay varies little across slopes. In Table 8, the runoff delay is dramatically shorter for High intensity storms than Low and Mid intensity. Again, delay varies little across slopes. These tables are important because they reveal a trend that implies little difference between runoff delay and module angle, showing that all retrofits behaved similarly under the same weather conditions. The main take-away is that sloped roofs can delay peak stormwater runoff.

Next, the team analyzed the relationship between storm categories and runoff delay for each module to see if there was any correlation (Table 9). A moderately strong correlation between intensity and runoff delay, and a weak correlation between size and runoff delay was observed. Plots can be seen in Appendices H and I.

Table 8 – Correlation between Runoff and Intensity/Size for Each Platform

	Control	15º	30º	45º
Intensity	0.7746	0.5603	0.7746	0.6968
Storm Size	0.3844	0.2138	0.3541	0.3389

Limitations

The experimentation performed on the green roof modules was limited by space, time, funding, and weather. The project space was limited to an area outside of the University of Maryland greenhouses. The size of that work space limited the size of the roof modules. The team decided to use a module size of 4 ft. by 12 ft. The rationale behind this choice was that 2 ft.

is the usual distance between roof supports; using a module width of 4 ft. allowed the experimenters to realistically simulate the weight distribution of a roof section. Ideally, the modules would have been full size roofs, but the width of the work space limited this. The module length was limited to 12 ft. It was more important to have a large length than width because the experimentation involved the flow of water down the slope. Besides controlling the module dimensions, the size of the work space also limited the total number of modules that could be built to four. This meant that no replication of the modules could be done to verify the results. It would also have been preferable to have a control roof module for each angle without any media or plants so that the amount of rainfall that landed on each different angle of the modules could be directly measured. Instead, the amount of water that lands on the roof was assumed to be proportional to the aerial area of each module because it was assumed that it always rained straight down.

The scope of the research project was also limited by the single, six month period during which testing was conducted. The relatively short growing period did not give the plants enough time to migrate and show their growing preferences. One of the original goals of the project was to find which plants thrived on the sloped modules, and, if apparent, which plants migrate to different heights along of the slope according to moisture content preferences. Because of the limited growing season, this original goal was not possible; instead it was noted anecdotally by the experimenters which plants did best on which modules. The question of plant location preference will be explored in future research by the University of Maryland Plant Sciences department, as the modules will remain intact for future projects. The limited amount of time for plant growth might mean that the plant roots were not able to fully establish. This might have meant that the roots were not able to access the water stored in the media. If this is true, the roofs will likely become more efficient at holding water over time, and the data presented in this thesis is representative of the early phases of plant establishment. The project time was made even scarcer by setbacks in media development. The original media chosen for the modules, Growstone, had to be abandoned due to numerous issues with plant growth and module construction. Many tests and experiments were done on the Growstone prior to this decision, so changing the media meant a good deal of time was lost.

The project scope was also limited by the available funds. The experiments could not be performed on full scale roofs because the cost of materials would have been much higher and a much larger work space would have to have been used. Like the work space size, fund availability limited the amount of trials to one and made the creation of control modules impossible.

The weather restricted the applicability of the project's results to climates similar to the location of data collection (College Park, MD). The test modules were located outside, so they were subject to the natural weather; the frequency and intensity of weather events was not controlled. Instead of being a limitation, this increased the external validity of the findings because, in practice, green roofs would be outside in erratic weather as well. However, because the data was only in 2014, the results may not be an accurate representation of all different weather patterns that could occur in future years.

Certain limitations affected the design of the methodology for moisture content data collection. The 5TM soil moisture and temperature sensors have an accuracy of ±3% volumetric water content for porous mediums. This accuracy also depends on the achieved correctness of the calibration for the rock wool material in which the sensors are placed. This accuracy limited the ability of the team to measure minute changes in volumetric water content. Uncertainties within the testing apparatus also limited the ability to draw conclusions from the data. The team was uncertain about how the location of the soil moisture and temperature sensors relative to the rock wool sheets affected the readings. Some probes were placed near the top of a rock wool sheet while others were placed towards the bottom. This could have caused inaccurate readings due to the possibility of water pooling at the bottom of the sheets. Water may not have ran evenly down to slope, moving down the sides instead of the center, where the probes were located. Further testing would be required to evaluate this. More uncertainty arose from the plants themselves. The team was unsure of whether or not the plants had fully established a root system that penetrated through the capillary fabric. This uncertainty limited the ability to make conclusions regarding the effects that different plants had on water transpiration from the modules. Certain plants may not have been given enough time to grow before data was recorded.

Focus Group

Introduction

In addition to assessing the team's engineered green roof system, it was important to determine the marketability of the design, and general interest of homeowners in installing green roofs. Current research identifies focus groups as instrumental keys to more in-depth exploration of attitudes around adopting green behaviors (Vernon et al. 2003; Flamm and Agrawal 2012). Additionally, researchers such as Bryant and Bailey (1991) have recognized the importance of using focus groups throughout the development of a new program, such as the development of the team's novel sloped green roof retrofit.

To this end, team SO GREEN conducted two sets of focus groups— the first, Focus Groups A, was conducted before the construction of the modules to inform the design, and then Focus Group B was held one year after construction to get feedback on the modules. These focus groups consisted of members of the local community, and the team's objective was to receive input on research and design, as well as gauge general interest in green roofing as a sustainable home improvement and stormwater management practice. Inviting participants back from the initial focus group to the second round allowed the team to gain valuable feedback on the design and lingering resident concerns, while the inclusion of new participants offered a valuable new perspective.

Assumptions

Team SO GREEN assumed that those who participated in the focus groups, donating their time with minimal compensation, were already interested in green roofs or the general idea of sustainable living. This is likely to lend response bias to the focus groups, and the tastes of the participants are not necessarily representative of the general public. This bias arose because all of the subjects that volunteered had some lay education on and interest in green roofing, despite not being required to have previous knowledge on this topic. However, if the number of people with a passion for sustainability and interest in implementing SO GREEN's design steadily increased, eventually a tipping point would be met where the idea would become well-known and socially accepted (McKenzie-Mohr 2010).

Methods

Focus Group Structure

The first step the team has to take was to recruit focus group participants. The thirteen participants in both focus groups were recruited through convenience sampling in community email listservs in Prince George's and Montgomery Counties in Maryland, advertising for homeowners interested in retrofit designs for residential green roofs. In particular, the areas around the University of Maryland campus were targeted. Additionally, word of mouth advertising, referrals, and flyers were used to attract participants. During both rounds, participants were provided a catered meal as compensation for their time, and participants who engaged in both the first and second rounds received $25 for returning.

Each session was facilitated by one primary facilitator with two co-facilitators. Focus groups were semi-structured, beginning with a set of questions but allowing conversation to flow and questions introduced by participants to be discussed with the facilitators and participants. All questions and discussions throughout the duration of the focus group were audio recorded. After the conclusion of each round of focus groups, team SO GREEN transcribed the recordings for coding and analysis. General categories of findings were first developed from review of focus group notes and content in transcriptions, using a grounded theory approach emphasizing coding as an emergent process (Charmaz 2006). After review, transcriptions were parsed again, highlighted, and grouped for final categorization and analysis of results.

Focus Group A

Focus Group A was conducted in April 2013. Participants for the first round of focus groups (n = 12) were split into two sessions based on availability. Before the group, participants self-identified their level of knowledge about green roofs from a scale of 1-5, with one being no familiarity with green roofs and five being a professional in the green roof industry. Participants reported a mean familiarity score of 2.67 (SD = 1.07).

Opening questions were utilized at the beginning of the focus group to gauge the general interest in green home improvements. One such question was "How much do you consider the environmental impact when renovating your home?" Other key questions included: "What are the most compelling reasons that you would get a green roof?" "What do you see as the biggest drawbacks to installing a green roof?" "How much would you be willing to pay to install a green roof retrofit?"

The team sifted through the recordings of both initial focus groups and found several emergent themes which were coded into the following categories:

- Consideration of environmental impacts in home improvements
- Appealing aspects of green roofing to consumers
- Level of personal interest in installing a green roof
- Opinions about green roof design (how it should look, feel, etc.)
- Financial considerations
- Any other noteworthy comments

All that was discussed during the focus group became valuable in determining homeowner opinions on green roofs, as well as informing the sloped retrofit design.

Focus Group B

Team SO GREEN conducted the second focus group in fall 2014 after the modules had been established and while data collection on moisture content and the irrigation system was ongoing. The team invited participants from Focus Group A to continue to learn about the team's research and provide feedback on the development of the design. Returning members were offered an incentive of $25 in addition to the catered meal during the session. Additionally, new participants were invited via the same listservs that were used in initial recruitment.

During the development process, Team SO GREEN identified several goals of the second round focus group:

- Investigate maintenance concerns
- Present and evaluate costs of green roofs (including tax incentives) to homeowners to elicit opinions
- Investigate the importance of appearance of the green roof for homeowners
- Determine the importance of community impact
- Investigate whether homeowners recognize green roofs in the area and have an opinion on them

Again, three team members conducted the focus group and three homeowners participated (n= 3), two of whom were returners. To begin the focus group, participants were shown the team's green roof modules. Participants were then asked for their initial reactions and whether the green roof modules differed from their expectations. Questions included "What appeals to you aesthetically?" and "Does the slope make a difference?" Returners were asked

"How does this differ from what you had imagined?" while the new participant was asked "How does this differ from what you expected?"

Following the module design feedback period, two team members gave a brief presentation on the design and costs of the team's green roof system, as well as rebates available in local jurisdictions. After the presentation, key questions asked included "How much would you be willing to pay to install the green roof retrofit?" "How much maintenance would you be okay with?" "What concerns do you have with plant growth, or seasonal changes?" "What would your neighbors think if you got our green roof?"

In the same manner of Focus Group A, discussion during Focus Group B was recorded using an audio recorder and transcribed by a sub team of five group members. Important comments and questions were coded into six emergent categories:

- Participants' consideration of environmental impacts when making home improvements
- Aspects of green roofing that consumers find appealing
- Participants' level of personal interest in installing a green roof
- Homeowner opinions about green roof design (i.e. how should it look, etc.)
- Financial considerations
- Comments and opinions on SO GREEN's roof (shown at the beginning of the focus group)

Any other comments deemed relevant or important were also noted.

Results

Focus Group A

The participants indicated that the increased cost of green roofs compared to traditional roofs and lack of familiarity with green roof systems are the two major barriers to installing green roofs. Moreover, the homeowners indicated that interest in sustainability, tax credits, and novelty are the primary motivators for their interest in green roof installation. The focus group also yielded additional suggestions and insights regarding design preferences and marketability for green roof systems.

Cost Considerations

The largest perceived barrier to installing green roofs was the greater cost associated with installing and maintaining a green roof system. Homeowners differed on how much more they would be willing to pay for a green roof than a traditional roof, based on personal factors involving their lifestyle and home. Many shared the sentiment that green roofing was attractive but not entirely feasible yet. As one participant stated, "I would be willing to pay a little more, but not orders of magnitude more. And then I factor in how much am I paying versus how much more work am I having to do." Another participant noted "I'd love to do Green whenever possible, I'm always under the assumption that it's gonna be cost effective in the long run, but really there just aren't options."

The participant's comments, like those of many others, also highlights a recurring theme of considering the potential cost savings that green roofs can provide with energy costs: "The energy efficiency is the economic impact, but a cooler attic and therefore a cooler house is huge." Another member offered "if it saves us money, like with an electricity or heating cost, I think we'd do it especially if it wasn't too expensive, but I'm not gonna go way out my way and expensive to do something. It's my bottom line that I have to consider."

In addition to the savings related to energy, tax breaks and increased roof longevity were perceived as financial incentives to invest in green roofs. One participant remarked "The idea of putting on a roof that'll last twenty-five years. My gosh, I'm sold. Because if I think, hmm, twenty-five years, so that saves us $8,000 times two, so $16,000," in reference to the alternative of getting a shingle roof replaced. Tax breaks and government incentives were also repeatedly mentioned within cost consideration, comparing green roofing to other incentivized environmental actions such as installing energy efficient windows: "And if there aren't the kind of tax benefits, you wanna do as much as possible but, you know, when it comes down to you know will I get credits for putting in new windows? Yes, okay, we put in the new windows." Moreover, the tax benefits need to be significant enough because as one participant concluded, "Even with the tax deferment and the help, they were still cost prohibitive for most people. It just didn't make sense, well it's way too expensive and it takes so long to get your return."

Lack of Familiarity with Green Roofs

A common theme highlighted in the focus group was the lack of concrete understanding of a green roof's benefits, especially in the case of benefits that are related to sustainability. One of the participants who self-reported an industry professional level of knowledge about green roofs stated:

> The problem is, you know, the benefit of water runoff is not something that the homeowners sees, what the homeowner sees is energy efficiency and that is a little bit hard to measure, you know it is kind of hard to say if you put a green roof on a home you will save $10,000 in three years, it's hard to measure. I think that if you can put a number there and prove that, I think that would help a lot. To do it I don't think there are many people that would pay 30 percent more on top of this maintenance cost.

Another participant remarked that she would not be comfortable putting a green roof on a large, visible, valuable structure such as her house, but might be if she had first installed a green roof on her shed and gained a better experience and understanding of a green roof without taking too great a risk. A similar perspective was proposed by another participant, who offered "If they're almost modular-like structures you can build and in some way try out. You know, just in small pieces. So you can feel like you're doing the right thing for the environment but you're not going over too far."

The lack of familiarity also brought questions about how green roofs are perceived in society as a whole. Resale value of homes were generally perceived by participants to decrease for having a green roof, except for one participant who believed it could increase resale value in her sustainability-focused neighborhood. Participants also believed that homeowners associations would be barriers to green roof installations, whether limiting green roofs to only non-visible roofs such as in the back of the house, or forbidding green roofs altogether.

Social Perception of Green Roofs

Participants noticed potentially positive social effects of installing green roofs. One participant, in addition to discussing the energy and cost benefits, added that "This may be minor but bragging rights is nothing to waive away completely." Another offered, "Yeah if it looks terrible, your neighbors aren't gonna be happy, but if it looks amazing and if you have like a sign in your yard and people are stopping and looking and you know you're kind of a testament to this new technology, then I think that that could be a really good thing and a good thing for water quality. You know an opportunity to have a good conversation about water quality."

In discussion about the community aspects of green roofing as a sustainable home improvement, many participants noted concern for future generations and overall community health as reasons to pursue green roof installation. One member offered a thought about community developers, suggesting "If they can use the green roofs as a way to mitigate other work they'd have to do on the side to collect stormwater, then it might be to their benefit. So the question is what kind of community are you developing and who's buying into it and how much will they pay?" Others agreed that "So as far as I'm concerned, it's an investment in the property. To say we won't be there the entire time, but it can be used as an incentive for hopefully whoever wants to buy the house."

Other Considerations

Sets of residential buildings such as townhouses and row houses were seen as potential markets that would have a greater impact on mitigating stormwater impacts than single-family homes. As one participant put it, "Imagine having some of these roads here with these row houses and they're green. My gosh that would be so so marvelous." Along similar lines, some homeowners with yards did not see how using green roofs would be any more beneficial than letting water run into the yard, especially for the cost.

Longevity and the overall sustainability impact of protecting children's futures were noted by homeowners as incentives to pursuing green roofing. Participants noted different habitats that vegetation could offer to increase biodiversity, including to bugs, birds, and butterflies, as well as the potential for using native plants or even edible vegetable gardens through green roofs. Increased efficiency through insulation, reduced flooding, energy efficiency in the home, and costs of heating and cooling were noted as incentives. Other benefits discussed included the pleasing sight of green roofs and ecological payback: "I think it also provides a pleasing sight when you can look across I think in a large city and see a green roof."

In consideration of the design for SO GREEN's sloped retrofit system, participants noted maintenance as the largest concern. Cost was also tied in to the consideration, including the safety of the homeowner being on a sloped roof, compared to the cost of hiring a roofer for potential occasional maintenance. Modular systems were preferred by participants for their perceived ease in installation, especially if a homeowner decides that he or she no longer wishes to have a green roof. Load bearing weight, the applicability to older roofs, concerns with installation, fitting into the neighborhood, the appearance of dormant plants in the winter, and resale/property values were also mentioned as drawbacks. Finally, the potential to collect rainwater in barrels and grow vegetables were suggested as elements of design to the retrofit sloped green roof system.

Focus Group B

Three respondents were ultimately present for the second iteration of the focus group. Two of the members were returning participants from the first round, and one was new to the project. All three participants self-identified having medium knowledge about green roofs, rating their knowledge at a three on a scale of one to five.

First, focus group members saw the experimental modules and responded to the aesthetic appeal of the team's green roof design. All three participants commented on the percent of vegetation cover, noting that the more uniform distribution of plants across the flat and 15º modules made them more visually appealing than the sparse cover of the 30º or 45º panels. One participant stated "I like the way the lower one had more vegetation, and I thought that one looked good. I would be happy to have that one. The higher ones – I wouldn't actually be worried if it didn't have any vegetation at all, because I don't think roofs are that attractive anyway." Many of the concerns that arose also centered on maintenance of higher sloped roofs, including gutter cleaning, the accumulation of leaves, or media blowing off the modules. Participants noted how these maintenance issues would affect the visual appeal of sloped green roofs, affecting the vegetation cover and the overall aesthetic.

Maintenance and Cost Concerns

Overall, participants identified concerns over maintenance and cost as two of the major drawbacks to implementing sloped green roofs. One participant was concerned with having to go on top of her roof, or else needing to hire someone to do occasional maintenance, stating that "it's those kind of logistics that, for me, [mean] it's not an attractive financial option." Part of the cost and maintenance consideration included the longevity and durability of the roof, with participants stating that a roof that is guaranteed to last for a longer time would be more appealing for homeowners for the lower labor investment over the lifetime of the roof. The sentiment was that unlike a yard, which homeowners will "fuss" with, "most people just want to put their roof up there and walk away." One participant stated "to me, it's as little maintenance as possible that would make it really attractive and make people decide 'Okay, I'm willing to fork over extra money.'" It was also stated that installation would be easier if the roof was in palettes, "you know, where the roofer could just take it and plot it on the roof," rather than as a contiguous system, similar to a sentiment expressed in the first round of focus groups.

At the same time, participants were surprised by the team's cost estimates and agreed that if the financials were as low as calculated, cost would be less of an inhibiting factor than they had previously assumed. From the team's presentation, participants were impressed by the low cost but felt that in the actual market, the additional cost of labor and commercial markup would still make it more expensive and therefore less feasible. Participants also spoke of the incentives that encouraged them to install green roofs, particularly financial incentives in the form of rebates offered by the government. One homeowner who lived in a community that was excluded from local incentive programs expressed her frustration with the lack of rebates, stating that "I could pave my whole yard and I would still pay the same amount, there's no incentive."

Public Perceptions of Green Roofs

Consideration of one's social impact also factored into the opinions that focus group participants shared. In the focus group, a large appeal of installing green roofs was certainly in the environmental impact. One participant stated that the most compelling reason for him was "the idea of trying to reduce runoff and pollution and be more sustainable," while another participant spoke of “the notion that everyone’s gotta do their part for the environment.” Focus group members spoke positively of the perception of being ahead of the curve in green advancements, and the pride of potentially invoking neighbor envy, or the “ego stroking” of being an early adopter, similar to results in Focus Group A. However, it was noted that the opinions of neighbors might not be relevant if the roof was not visible publicly, which might also mean homeowners are less willing to spend money on it. Consideration of neighbor’s opinions were again addressed negatively as well, particularly in the case of homeowners associations or coding issues that could serve as barriers to green roof installation. Another factor that all three participants agreed on was the potential effect on resale value, both as a social and financial consideration. Participants stated that while the current homeowner or neighbors might see the green roof as a positive investment, installing a green roof could potentially affect future marketability, which is a risk factor for undertaking the project.

Ultimately, participants agreed that the idea of a green roof even for pitched roofs would be more appealing in several years. One participant stated that “I would be willing to pay 20-30% more for a green roof,” but currently, market costs of a commercial green roof are prohibitive because there is a perception that they are closer to double the cost of a regular roof. There was concern given that the industry is still relatively new, and signing on to a trial system such as team SO GREEN’s modules would be “a huge investment in something that’s not proven.”

Discussion

Through both sets of focus groups, participants echoed that cost was a large limiting factor in deciding to install a sloped green roof retrofit. Like other sustainable home improvement projects, participants largely agreed that they would be willing to pay more for a green roof versus a regular roof, but the actual premium that a homeowner would be willing to pay on the product would be highly variable. Participants considered the availability of rebates or incentives offered by the government or local watershed groups, and even if the financial offset offered was nominal, the motivation of incentives was appealing. Participants were also surprised by the cost of the team's engineered retrofit system, which will be discussed in a future section.

Interestingly, participants did not generally speak of individual concerns or benefits beyond cost considerations. Concern for the environment, water quality, benefits to future generations, increasing community green space, and improving air quality were all lauded as reasons to pursue green roofing, even with potentially higher costs. The idea of "doing one's part" was reflected among all the sessions, with participants demonstrating a high awareness of socioecological benefits of green roofing. However, on the individual level, discussion of benefits was limited to reduced energy costs and less investment of time and money in roofing as a home improvement concern. Individual benefits from seeing green landscapes, stabilizing and lowering indoor air temperatures, improving local water bodies, or having improved air quality around the home were less frequently or not mentioned at all as incentives for adopting green roofs, though all of these benefits were presented in the introductory presentations. This may indicate a gap in the education and understanding of green roofs, or else reflect that those interested in installing green roofs would do so for the benefit of the environment and society as a whole rather than individual gain, provided it was financially feasible.

The one exception to this finding was socially, where green actions were viewed by the focus group members as a positive reflection of the individual to others. In each group, the choice to install a green roof was discussed as a reflection of values, physically manifested and visible to one's community. Generally, part of the desire to install a green roof intimated by participants was to be ahead of the Joneses, and being proud to demonstrate the technology of green roofing as a reflection of the homeowner's forward thinking. However, it was noted that being cutting edge could also lead to judgment from some neighbors, along with concerns of homebuyers if the residence was put up for sale, and whether homeowners associations would allow green roofs. These ideas of how society views green roofs showed the need for widespread knowledge and education about green roofs, such that they become familiar to the general public and relevant institutions in the same way that other green technologies have in recent years.

Finally, participants responded positively to the specific sloped retrofit system designed by the team. Focus group members noted that the extreme slopes were less appealing, but that the appearance of the plants was not off-putting to the green roofs. The slope also introduced concerns with maintenance, particularly for accumulation of leaves or snow with the unique honeycomb design of the cells. Participants from both rounds mentioned the appeal of modular or tray retrofit systems, for both perceived ease of installation and replacement if the roof was unsatisfactory.

Future Directions

Given the dearth of current research on perceived barriers and incentives to choices in sustainable living, this study in Team SO GREEN's research served only to fill a small hole in the sizable gap. The focus groups, limited in their size and sampling, were indicative of the thoughts of only a small portion of the population, rather than the common person's opinion of green roofing and other green home improvements. To this end, significantly more work needs to be done in investigating consumer consideration in choosing sustainable home improvements, particularly when it comes to green roofing. Empirical studies to assess the interest, current barriers, and potential incentives to adopting sustainable behaviors by the average homeowner could greatly improve marketability and adoption of important green innovations.

For sloped green roof systems, the nominal research to date has focused on development of the technology rather than how consumers can be convinced to buy in. Without empirical research in the usability of these technologies and buy-in from adopters, further development could be moot, whether in green roofing or other sustainable technology industries like green vehicle ownership (Flamm and Agrawal 2012). Particularly for retrofit systems, the interest from homeowners (as well as businesses, institutions, and others with sloped roofs) including cost comparisons and ease of installation should be further explored for maximum effectiveness of continually developing green technology.

Irrigation System

Introduction

The most efficient irrigation system determined by experts in the field "is one that applies the lowest volume of water to evenly irrigate crops in a way that is both cost- and energy-efficient," (Ristvey and Lea-Cox, 2015). The decision of whether or not to irrigate a green roof is a highly debated subject among green roof professionals. Either side of the argument presents important pros and cons. The overall pro of irrigation is that water can be pumped back up to the roof and circulated through the system. This will lead to heightened evapotranspiration and reduced runoff, which is a major goal of the green roof system. Another pro is that green roofs with an irrigation system are more likely to have improved plant coverage and root development (Rowe et al. 2014). This increased plant coverage will heighten the aesthetic quality of the roof, making it more desirable for homeowners. This increased coverage will also initiate deeper root development of the plants and allows for better water retention. A con associated with irrigating green roofs is that rainfall water availability varies among different regions and climates. Regions that experience droughts would need to irrigate with tap water, an expensive resource. Rain harvesting is a potential irrigation supply for these regions, however depending on the severity of the drought rain water may not be sufficient. Therefore the climate and average rainfall should be checked prior to making an irrigation decision.

There are three major forms of irrigation for green roof systems: overhead, drip, and sub-irrigation (Rowe et al. 2014). Drip irrigation, as shown in figure 29, utilizes a network of tubes that bring water throughout the roof to each of the plants. It is effective for farming as the surrounding soil doesn't need the water and therefore only applies the water the roots need. This minimizes the water that is released out of the system. This is not as effective for sloped green roofs as the goal is to retain moisture throughout the substrate media and not just where the plants roots are found. Spreading water throughout the entire roof will allow for greater evapotranspiration.

Once the decision has been made as to whether or not irrigation is worthwhile for a green roof system, the designer must determine how the green roof's irrigation will be monitored. New technologies have made irrigation monitoring even easier as there are many factors that come into play when designing an irrigation system (Ristvey and Lea-Cox 2015).   Novel systems are beginning to employ moisture probes in order to create a feedback loop in the system (Ristvey and Lea-Cox 2015). When the moisture level in the green roof drops to a certain value, the irrigation system will turn on and begin to distribute water to the roof. This means that humans do not need to monitor the irrigation system as the system will irrigate automatically.

Figure 29. Plants and Irrigation System (Driptech 2012)

The next form of irrigation used for green roofs is sub-irrigation. Sub-irrigation, as shown in figure 30, delivers the water to the roots of the plants directly by using a wick system underneath the media (Rowe et al. 2014). Transporting the water underneath the system directly to the roots ensures that water is not wasted in the process. This was determined to be more effective than the drip irrigation process, however it still only brings moisture to portions of the media. Sub-irrigation would be a prominent irrigation method for water-strained regions of the country due to its efficiency.

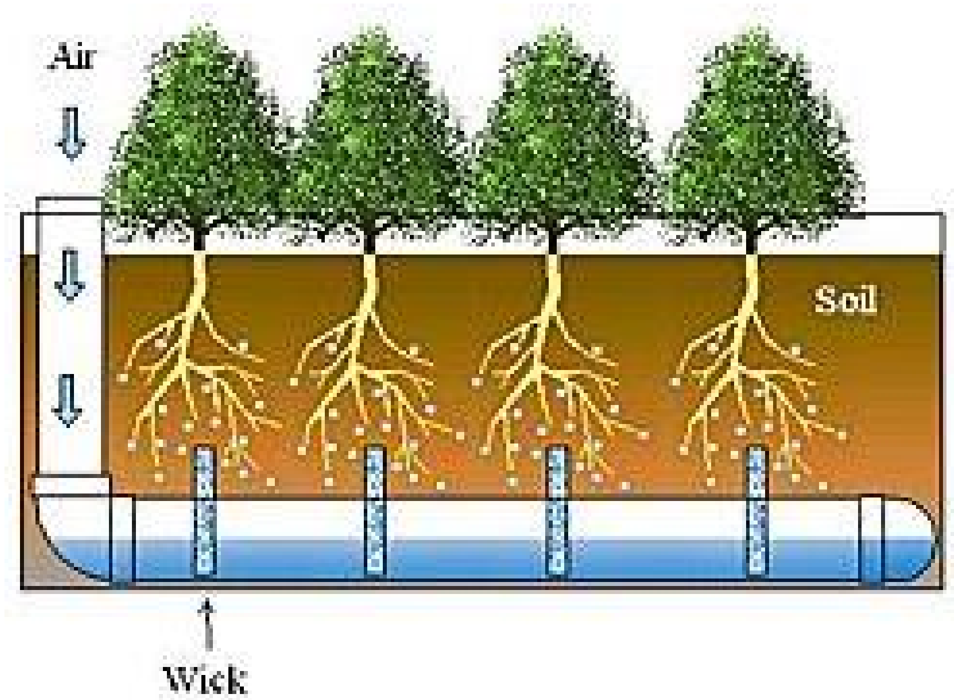

Figure 30. Example of a Subirrigation System (Inside Urban Green 2015)

The last form of irrigation is the overhead irrigation system, as shown in figure 31. This system is the most effective form of irrigation for green roofs (Rowe et al. 2014). It distributes water to all parts of the media which means that the green roof will act hydrophilically and retain more water (Griffin 2014). However, this system of irrigation uses the most water. Therefore it would not be as beneficial in dry areas as the system would need to pump in clean, treated water to continue to irrigate.

Figure 31. Overhead Irrigation System (Green Roof Tech 2013)

After the green roof system was established on the four modules, the team implemented an overhead irrigation system to the 30º module. The 30º module was selected for the irrigation system because it was the steepest of the slopes that had success with the initial green roof system. The team assumed that results on the 30º module would be further enhanced by the reduction of slope on the other modules. However, the lack of replication within the experiment limited the ability to draw quantitative conclusions. The same assumptions regarding the behavior of the rain previously made in the initial experiment still applied. Irrigation system data was only collected for three months which also limited the team's ability to understand how this system performs under various conditions. Because of the limited time period, the module never experienced conditions of a large storm, as defined by the number of rain and above. Therefore, conclusions were limited to the results of the behavior during small and medium events alone.

Methods

The implementation of the irrigation system began with the addition of a water collection system. A 55-gallon barrel was added after the gutter and rain gauges in order to store the runoff to be used later. A Rule Computerized Sump Pump (Rule Industries, Gloucester, MA) was then used to move this stored water to the top of the module. During the experiment, the timing for the pump to work was controlled manually. Future work could be done to implement a system that turns on the pumps automatically depending on the volumetric water content within the system. Three hose lines were connected to this pump, which ran vertically down the module. This allowed for even coverage of the system. Along each vertical line, 15 sprinkler heads sprayed a mist of the water onto the module to reuse the water. The use of the misting sprinkler heads allowed for a greater amount of the water to be released into the atmosphere through evapotranspiration. Any water that did not get released through evapotranspiration was then cycled back through the irrigation system again and pumped back to the top of the module until all of the stormwater was released.

Discussion

Team SO GREEN used the moisture content readings from each of the four ports to determine whether or not the irrigation of the 30º module was successful. Despite running the pump continuously after a storm event to cycle water through the system, there was no sign of difference in the moisture retention of the module. This was not what the team hypothesized as they thought that the module, specifically the rock wool would be able to retain more of the water being cycled through.

The team did not achieve the desired moisture retention sought in the prototype irrigation system. One possible explanation as to why the irrigation did not increase the moisture of the roof is in how the rock wool layers were positioned. The rock wool material had fibers running in one direction along the length and would allow more drainage depending on the orientation. The team believes that the orientation of the rock wool layer on the module allowed water to drain easily. Altering the orientation of the rock wool is one possible solution to increasing water retention.

The second source that was concluded to influence the minimal change in moisture content can be attributed to the hydrophobicity of green roof substrates. During an extended dry period, a green roof substrate will lose its water holding capability as it becomes hydrophobic (Griffin 2014). Griffin found that near volumetric water content of 8%, a substrate lose its ability to re-wet taking an extended period of time to saturate. Therefore it becomes difficult for the water to infiltrate through the substrate and stay contained in the media. The media may have been impacted by this process and therefore the water irrigating the module did not infiltrate as well as was intended. Choosing to use less organic matter will make for better substrate characteristics as organic matter tends to be a driving force in the hydrophobicity of a substrate (Griffin 2014).

The team's third hypothesis as to why the moisture of the rock wool did not increase in the sloped modules is due to the fine particles of the Greek pumice in the M2 media. These fine particles may have collected within the filter fabric layers and prevented water infiltration. No matter how much irrigation water was applied and circulated, it would not pass through the filter fabric to saturate the rock wool. The team's goal for the rock wool was to have water pass through the media layer and soak into the rock wool to be held and slowly released over time. A clogged filter fabric may have completely prevented the water from reaching the rock wool. A solution to this would be to screen the M2 media of small particles before putting it on the green roof.

Economics

Introduction

The team conducted an economic analysis on the implementation of their green roof design in order to better understand the feasibility of installing a green roof retrofit in a residential environment. Costs to consumers not included in calculations are any structural modifications to an existing house, permits, or zoning fees. Economic calculations are limited to this specific green roof design, and only include materials. It is assumed here that a green roof retrofit is allowable and does not necessitate any structural modifications to existing homes. All calculations are based on the criterion that the green meets all parameters and can be installed.

The team defined a cost effective roof as a retrofit that costs less than $10 per square ft. Since residential green roofs are not common in the market, there is no real industry cost average. Designs vary, and differing amounts of material and included technology make each green roof unique. Since cost is difficult to determine, the benchmark of $10 was necessarily based on the national average for shingle roofs. The reason for this figure is that it is greater than the average cost of a shingled roof per square ft. According to Costwyse (2015), that cost is between $5.80 and $9.50 per square ft. Garrett (2007) also examined typical green roof costs and found that the cost per square foot on average is $4.95 to $18.56. This figure is adjusted for inflation (US Inflation Calculator 2015). Ten dollars per square ft. is slightly more than shingle pricing, and this is acceptable because rebates and intangible benefits a consumer would receive for buying a green roof would counteract the additional cost.

Objective

The implementation of tax incentives was also evaluated. Currently, more counties and locales in the state of Maryland are requiring annual taxes from property owners based on the area of impervious surfaces owned. Known as the "rain tax," this is an example of a negative incentive that encourages customers to find means of mitigating impervious surfaces. Typical annual fees range from $21 to almost $300, depending on property size and impervious surfaces located on the property (Fiscal and Policy Note 2015). A green roof is one such way of mitigating these taxes. There are a few ways of also receiving tax credits and becoming exempt from the rain tax. They include rain barrels, conservation landscaping, pavement removal, and native tree planting. If rain barrels are used in conjunction with the green roof design, the green roof retrofit would be eligible for tax rebates.

For consumer economics, the responses from the focus group were considered. Based on focus group feedback, cost versus value was the top deciding factors for homeowners as to whether they would actually utilize such a design. Tax rebates was one such factor, but overall cost had to be low enough in order to compete with cheaper roofing systems, like asphalt shingles. The green roof could be slightly more expensive, because it was regarded by the focus group as contributing positively to the environment. In the end it was decided that a green roof retrofit must not only be lightweight and simple to install, but also cost effective.

Methods

In order to make an accurate cost comparison between installing a shingle roof or a green roof retrofit, calculations are based on 1500 square foot roofs. This means that there are shingles, nails, and a waterproofing layer to be accounted for in the case of shingle roofs. Accounted for in the green roof retrofit are waterproofing membrane, flashing, drainage layer, rock wool, filter fabric, substrate, LSG, plants, steel edging, and aluminum edging. To calculate perimeter for the aluminum and steel edging, a roof size of 60 ft. long by 25 ft. wide was selected. To calculate perimeter for the aluminum and steel edging, a roof size of 60 ft. long by

25 ft. wide was selected. Everything was measured in square ft. with the exception of substrate (cubic ft.), flashing (ft.), and aluminum (ft.).

Calculations for the 1500 square foot shingle roof were obtained from Mid-Atlantic roofers, like Swaim. Coupled with the figures from Costwyse (2015), a total cost was calculated. For the green roof, cost per unit of each component was multiplied by the dimensions of the 1500 square foot roof to determine individual item subtotals. These subtotals were summed to generate a grand total cost. After the grand total was calculated, the final cost was divided by 1500 square ft., which yielded the final cost per square foot for the green roof retrofit. All calculations can be found in Appendix G.

Results

The cost of a 1500 per square ft. equivalent of the green roof system developed in this project is $10.05 per square ft. This almost met the goal cost of $10 per square ft. which is the estimated cost of current extensive green roofs according to the EPA and is also closer to the cost of traditional roofs which are estimated to cost $8 per square ft. Additional features for enhanced water-holding, evapotranspiration, and plant survivability including the cistern-recirculation system, and sensor system would cost approximately $1200 and $1500 respectively. For the 1500 per square ft. the total system would cost approximately $11.85 per square ft., and can be seen below in Table 10.

Table 9 – Cost of Green Roof Designs

Roof Type	Cost ($/ft^2)	Cost w/ Labor
Shingle	4.70 – 6.75	5.80 – 9.50
Green Roof	4.95 – 18.56	—–

SO GREEN	6.93	10.05
SO GREEN w/ Irrigation	8.73	11.85

Conclusion and Future Directions

Research Summary

SO GREEN's research project consisted of four main sections: 1) moisture content and runoff data collection and analysis of sloped green roof modules, 2) the determination of homeowner interest in green roof installation through focus groups, 3) the design and construction of an irrigation system that could be used in conjunction with a green roof to reduce and repurpose runoff, and 4) the analysis of sloped green roof economic viability.

The modules were built to realistically mimic typical roof designs and weight loading. The four different module angles, 2˚, 15˚, 30˚, and 45˚, were chosen based off a range of common roof designs. The substrate was developed to be lightweight and nutrient filled for plant growth. The particle size was determined to allow water to flow through the substrate and not drown the plants, while still slowing the water and absorbing it to reduce runoff. Several common Sedum varieties were chosen and planted based on their survival capabilities in the Maryland climate. Moisture content data was collected using moisture probes in the rock wool layer of the roof design. Runoff volume was collected and measured using tipping rain gauges.

The team held two sets of focus groups over the course of the project. The first was held before the green roof modules were completely designed, and its purpose was to inform the module design. The second set was held after the modules had been built and the team had some preliminary impressions to share with the focus group. This allowed the team to receive feedback from homeowners on the completed design. Both sets of focus groups provided valuable information about general interest in green roofs and sustainable home design. All focus group members were found through convenience sampling of the local community. After an initial presentation of SO GREEN's research goals and progress, the focus groups were run in a discussion format. The facilitator presented questions for the group to discuss, and their answers were recorded by a note taker. Those notes were then synthesized into a list of overall trends in the discussions and meaningful takeaways.

The irrigation system was designed to collect runoff and redistribute it to green roof. The objective was to reduce overall runoff and increase the evapotranspiration occurring on the roof. The overhead irrigation system was implemented on the 30˚ module. Three hoses were connected to a water pump and ran vertically down the slope. The pump moved the runoff collected at the bottom of the slope back up to the top, where it was distributed back to the roof using the three hoses and a number of sprinkler heads.

An economic analysis was performed to compare the experimental green roof design cost to the cost of a traditional shingled roof. The analysis was limited to the costs of materials, and possible savings from rebates were considered. Information from the focus groups was also used to determine what cost efficiency homeowners would consider worth the extra work and maintenance involved in using a green roof.

Module Design

The team attempted to design the best retrofit green roof to be placed on existing sloped roofs. In designing the module, the team divided into two phases: Phase I and Phase II. In Phase I, an ideal substrate was created based on weight, granulometric distribution, durability, porosity, and plant growth capabilities. The team concluded that the substrate containing M2, Greek Pumice, and a minimal amount of organic matter is the ideal substrate for the module. In Phase II, the team designed and constructed four 12 ft. by 4 ft. modules at each of four different slope options: flat or 2º, 15º, 30º, and 45º. These modules were designed based on king post truss type, and each module included five different layers: EPDM waterproofing membrane, drainage layer, rock wool, filter fabric, and LSG. The team then selected a variety of Sedum plants to be tested: *Sedum album*, *S. sexangular*, *S. kamschaticum*, *S. reflexum*, *S. hybridum* and *S. spurium,* and concluded that the *Sedum kamtschaticum* established most successfully.

To study the performance of the modules constructed, the team determined the weight of the module, plant coverage, volumetric water content, and runoff measurement. The team conducted the weight analysis of the 1' x 1' module of the roof component system. In this analysis, the team found the final dry weight to be 9.81 psf and saturated weight to be 16.08 psf, reaching the goal of weighing less than 10 psf dry weight and 50 psf while saturated. Based on the plant coverage study, the team concluded that the control module performed the best with the most plant coverage.

Performing correlation analysis, the team evaluated volumetric water content and runoff delay time of the modules. The sensor at the bottom of each module showed that for all storm sizes, the sloped modules maintained a much lower VWC than the control module, while there was no apparent difference in VWC amongst sloped modules. Also, volumetric water content was noticeably different between the control and sloped modules for all levels of storm intensity. At the end of this study, the team concluded that the control module is more effective in retaining water after precipitation than sloped modules. In regards to the runoff volume, there were no apparent differences between the modules. The team therefore concluded that the sloped modules performed about as effectively as the control module in delaying stormwater runoff. This contradicts Oberndorfer's suggestion that sloped residential roofs are not a worthwhile investment on a small scale (2007).

Focus Groups

Overall, homeowners would be willing to the premium for a green roof, although the actual amount varies person to person. The team's focus groups spoke to some of the perceived barriers and incentives to investing in green roofs, particularly on residential sloped roofs. Cost was a major concern, including the potential cost of maintenance, but was mitigated by the potential for less lifetime investment in roofing and energy savings that a homeowner might see for installing a green roof. Participants also noted the appeal of tax and rebate incentives for installing green roofs.

Beyond cost considerations, participants mainly noted incentives for installing green roofs. Participants mentioned creating more green space and natural habitats, improving air and water quality, and requiring less lifetime maintenance. A strong incentive noted among the participants was doing one's part for the environment and future generations, as well as how neighbors and friends would positively perceive an individual for investing in sustainable home improvements. However, this was also viewed as a potential disadvantage for home resale values by homebuyers who were less educated on or interested in green roofs.

In regards to design, the 45º module was perceived as too extreme. Sparse vegetation cover, the potential for more accumulation of snow or leaves, and safety concerns were all discussed as perceived disadvantages to more extreme sloped roofs. Participants mentioned safety concerns that might prevent self-maintenance of the roof, and add to the cost of the roof for paying someone else to complete maintenance.

Economic Assessment

The team determined economic viability of implementation of green roofs by making a cost comparison between installing a shingle roof and a green roof retrofit. Analysis on Focus

Group A indicated that cost of green roofs in comparison to that of traditional roofs is a major barrier to installing green roofs. The team subsequently conducted an economic analysis of the green roof system the team developed and determined that the total green roof system of 1500 ft^2 costs approximately $13097.40, which is equivalent to $8.73 per ft^2. This cost met team's goal of under $10 per square ft., which is the national average for shingle roofs. Participants of Focus Group B agreed that this low cost encouraged them to install green roofs. The team therefore concluded that the team's green roof is economically viable.

Irrigation System

The team attempted a prototype irrigation system on the 30º module in an effort to increase evapotranspiration of plants by recirculating collected runoff. However, the system was unsuccessful, and saw no increased moisture retention from running the irrigation pumps. The results can potentially be explained through several different errors. First, rock wool may have been placed with the wrong orientation. Second, the team speculates that the hydrophobicity of rock wool likely led to the incapacity to retain water after a drying out period, and recirculated water running off the platform rather than being absorbed (Griffin 2014). Finally, the filter fabric may have become clogged by fine particles, creating a physical and chemical barrier for water to reach the rock wool underneath. Irrigation systems should still continue to be tested. Irrigation control is another future research objective. Moisture sensors can be integrated into the irrigation system. During periods of no rain, irrigation can by cycles automatically either by time or by moisture sensors in the media. Stored water can be easily released through evapotranspiration. These systems presently exist but would increase the cost of the roof.

Future Directions

There are many valuable future research avenues in both sloped green roof water retention testing and the psychology of sustainability. There are already plans for future runoff and moisture content research to be continued on the modules created for this project. They will continue to be used by team SO GREEN's mentor, Dr. Andrew Ristvey. This project has provided a foundation for future research using the modules, and will enable Dr. Ristvey and colleagues in his department to collect more accurate and long-term data. Long-term data will more accurately reflect the differences in survivability of different plants at different slopes, how season changes and weather affect water retention, and how storm intensity affects water retention. However, future research utilizing the sloped modules from this project is only applicable to the Mid-Atlantic region of the U.S. Future sloped green roof research is necessary in different climates and conditions, and the research should also include replications of each of the differently sloped modules.

Further psychology research should explore the barriers and incentives for installing sustainable home technologies. It should examine why it is not common for most homeowners to view runoff management as a best management practice, like they would saving electricity or water. In a more general research direction, future studies should be undertaken to find why people choose or do not choose to live sustainably. It is also important to learn more about what kind of incentives would change homeowners' practices so that those incentives could be applied to increase the use of green roofs and other sustainable home technologies. Such research would be vital to the creation of government incentives or taxes to encourage the adoption of sustainable solutions.

References

Alexandri, E., and Jones, P. April 2008. "Temperature Decreases in an Urban Canyon Due to Green Walls and Green Roofs in Diverse Climates." *Building and Environment* 43, no. 4 (April 2008): 480-93.

Anand, L. 2008. "Truss Design." Educational Portal for Polytechnic Students. Accessed March 13, 2015. http://www.ustudy.in/sites/default/files/truss_configurations.gif

ASLA Green Roof. Illustration. Flickr. 2013. Accessed September 8, 2013. http://www.flickr.com/photos/landscapearchitects/4384294767/sizes/o/in/set-72157623375752363/.

Barton, E. 2015. A comparison of organic matter types for use on extensive green roofs. Master Thesis. University of Maryland, College Park. Pp. 106.

Bianchini, F., and Hewage, K. 2012. "How 'Green' Are the Green Roofs? Lifecycle Analysis of Green Roof Materials." *Building and Environment* 48: 57-65. Accessed September 4, 2012. http://dx.doi.org/10.1016/j.buildenv.2011.08.019.

———. 2012. "Probabilistic Social Cost-Benefit Analysis for Green Roofs: A Lifecycle Approach." *Building and Environment* 58: 152-62. http://dx.doi.org/10.1016/j.buildenv.2012.07.005.

Blackhurst, M., Hendrickson, C., and Matthews, H. S. 2010. "Cost-Effectiveness of Green Roofs." *Journal of Architectural Engineering*, 136-43.

Bryant, C. A., and F. C. Bailey, D. F. C. 1991. “The Use of Focus Group Research in Program Development.” NAPA Bulletin 10 (1): 24–39. doi:10.1525/napa.1991.10.1.24.

Butler, C., and Orians, C. M. 2011. “Sedum Cools Soil and Can Improve Neighboring Plant Performance During Water Deficit on a Green Roof.” *Ecological Engineering* 37 (11): 1796-1803.

Castleton, H., Stovin, V., Beck, S., and Davison, J. 2010. "Green Roofs; Building Energy Savings and the Potential for Retrofit." *Energy and Buildings* 42, no. 10: 1582-91. Accessed August 27, 2012. http://dx.doi.org/10.1016/j.enbuild.2010.05.004.

Charmaz, K. 2006. “Coding in Grounded Theory Practice.” In Constructing Grounded Theory, 42–71. Sage Publications.

Claus, Karla, and Sandra Rousseau. "Public versus Private Incentives to Invest in Green Roofs: A Cost Benefit Analysis for Flanders." *Urban Forestry & Urban Greening* 11, no. 4 (2012): 417-25. Accessed January 28, 2014. https://lirias.kuleuven.be/bitstream/123456789/406655/1/10HRP30.pdf.

Coinnews Media Group. "Inflation Calculator." US Inflation Calculator. Last modified 2015. Accessed March 24, 2015. http://www.usinflationcalculator.com/.

Cook-Patton, Susan C., and Taryn L. Bauerle. "Potential Benefits of Plant Diversity on Vegetated Roofs: A Literature Review." *Journal of Environmental Management* 106 (2012): 85-92.

Costwyse. 2015. "Cost to Install a Shingle Roof." HomeWyse. Accessed March 13, 2015. http://www.homewyse.com/services/cost_to_install_shingle_roof.html.

DC Water. 2015. "Wastewater Treatment." DC Water. Accessed May 4, 2015. http://www.dcwater.com/wastewater/

Dunnett, N., Nagase, A., Booth, R., and Grime, P. 2008. "Influence of Vegetation Composition on Runoff in Two Simulated Green Roof Experiments." *Urban Ecosyst*, 385-98.

Emory Knoll Farms. 2015. "Sedum album." Green Roof Plants. Accessed March 24, 2015. http://www.greenroofplants.com/catalog/plant-catalog/viewplant/?plantid=569.

The Engineering ToolBox. 2015. "Weight Calculator - Roofing Materials." The Engineering Toolbox. http://www.engineeringtoolbox.com/roofing-materials-weight-d_1498.html.

EPDM Roofing Association. 2015. "What is EPDM?" EPDM Roofing Association. Accessed March 24, 2015. http://www.epdmroofs.org/what-is-epdm.

Fiscal and Policy Note, A. 773, 2015 Gen. Assem. (Md.).

FLL, 2002. Richtlinie für die Planung, Ausführung und Pflege von Dachbegrünungen. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau E.V. Bonn, 95 pp.

Flamm, B. J., and Agrawal, A. W. 2012. "Constraints to Green Vehicle Ownership: A Focus Group Study." *Transportation Research Part D: Transport and Environment* 17, no. 2: 108-15. http://dx.doi.org/10.1016/j.trd.2011.09.013.

Garrett, C., Klein, K., and Phelps, A. 2007. “Green Roof Design.” *AIA Best Practices*.

Getter, K. L., and Rowe, D. B. 2006. "The Role of Extensive Green Roofs in Sustainable Development." *HortScience* 41, no. 5: 1276-1285.

———. 2008. "Media Depth Influences Sedum Green Roof Establishment." *Urban Ecosystems* 11, no. 4: 361-72. Accessed September 1, 2012. doi:10.1007/s11252-008-0052-0.

Getter, K. L., Rowe, D. B., and Andresen, J. A. 2007. "Quantifying the Effect of Slope on Extensive Green Roof Stormwater Retention." *Ecological Engineering* 31, no. 4: 225-31. http://dx.doi.org/10.1016/j.ecoleng.2007.06.004.

Getter, K. L., and Rowe, D. B. 2009. "Substrate Depth Influences Sedum Plant Community on a Green Roof." *HortScience* 44: 401-07.

Getter, K. L., Rowe, D. B., and Cregg, B. M. 2009. "Solar Radiation Intensity Influences Extensive Green Roof Plant Communities." *Urban Forestry and Urban Greening* 8: 269-81.

Green Maryland. 2012. “Smart, Green, & Growing.” http://www.green.maryland.gov/mdgpi/8.asp.

Green Roof Plants. 2012. Accessed November 19, 2012. http://www.greenroofplants.com/catalog/plant-catalog/viewplant/?plantid=482.

Green Roof Research at MSU Department of Horticulture. 2009. Accessed August 15, 2012. http://www.hrt.msu.edu/brad-rowe.

Green Roofs for Healthy Cities. 2014. "Green Roof Benefits." Green Roofs for Healthy Cities. Accessed March 24, 2015. http://www.greenroofs.org/index.php/about/greenroofbenefits.

Griffin, W. N. 2014. *Extensive Green Roof Substrate Composition: Effects of Physical Properties on Matric Potential, Hydraulic Conductivity, Plant Growth, and Stormwater Retention in the Mid-Atlantic*. Doctorate Dissertation. College Park, MD: pp 172.

Grinde, B., and Patil, G. G. 2009. "Biophilia: Does Visual Contact with Nature Impact Health and Well-Being?" *International Journal of Environmental Research and Public Health* 6: 2332-43. Accessed August 25, 2012. http://www.mdpi.com/journal/ijerph.

Hodgson, Neal Evan. 2012. Interview. College Park, MD.

Jaffal, I., Ouldboukhitine, S. E., and Belarbi, R. 2012. "A Comprehensive Study of the Impact of Green Roofs on Building Energy Performance." *Renewable Energy* 43: 157-64. http://dx.doi.org/10.1016/j.renene.2011.12.004.

Jim, C. Y., and Peng, L. H. 2012. "Weather Effect on Thermal and Energy Performance of an Extensive Tropical Green Roof." *Urban Forestry and Urban Greening* 11, no. 1: 73-85. http://dx.doi.org/10.1016/j.ufug.2011.10.001.

Kohler, M., Schmidt, M., Grimme, F. W., Laar, M., Paiva, V. L. A., and Tavares, S. 2012. "Green Roofs in Temperate Climates and in the Hot-Humid Tropics--far beyond Aesthetics." *Management of Environmental Quality* 13, no. 4: 382-91.

Legislative Branch News. 2012. "Prince George's County Maryland." *County Council Creates Stormwater Management Retrofit Program*. Accessed October 15, 2012. http://cms.princegeorgescountymd.gov/PressReleases/default.aspx?itemid=754.

Lyandres, O., and Welch, L. C. 2012. "Reducing Combined Sewer Overflows in the Great Lakes." *Alliance for the Great Lakes*.

Magill, J. D. 2011. *A History and Definition of Green Roof Technology with Recommendations for Future Research*. Research report. N.p.: Southern Illinois University Carbondale.

Martens, R., Bass, B., and Alcazar, S. S. 2008. "Roof-envelope Ratio Impact on Green Roof Energy Performance." *Urban Ecosystems* 11, no. 4: 399-408. Accessed September 1, 2012. doi:10.1007/s11252-008-0053-z.

Douglas, M. M. 2010. "Social Norms: Building Community Support." In Fostering Sustainable Behavior: An Introduction to Community-Based Social Marketing. http://www.cbsm.com/pages/guide/social-norms:-building-community-support/

Niu, H., Clark, C., Zhou, J., and Adriaens, P. 2012. "Scaling of Economic Benefits from Green Roof Implementation in Washington, DC." *Environmental Science and Technology* 44, no. 11: 4302-08. Accessed August 26, 2012. http://pubs.acs.org/doi/abs/10.1021/es902456x.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R., Doshi, H., Dunnett, N., Gaffin, S., Kohler, M., Liu, K., Rowe, B. 2007. "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services." *BioScience* 57, no.10:823-833. Accessed May 5, 2015.

Ontop Internet Marketing Services. 2014. "What Kind of Trusses to Use for Different Roof and Ceiling Shapes." CortezColorado.net. Accessed March 8, 2015. http://cortezcolorado.net/what-kind-of-trusses-to-use-for-different-roof-ceiling-shapes/.

Ristvey, Andrew. 2012. Interview. College Park, MD. October.

Ristvey, Andrew, and John Lea-Cox. 2015. Precision Irrigation for Nursery and Greenhouse Crops. In: Total Plant Management of Herbaceous Perennials. University of Maryland Extenion Bulletin 359. 2015.

Rowe, D. B., Getter, K. L. and Durham, A. K. 2012. "Effect of green roof media depth on Crassulacean plant succession over seven years." *Landscape and Urban Planning* 104 (2012): 310-19.

Rowe, D. B. 2010. "Green Roofs as a Means of Pollution Abatement." *Environmental Pollution* 159, nos. 8-9: 2100-10. Accessed August 13, 2012. http://www.scribd.com/doc/46939984/Green-Roofs-as-a-Means-of-Pollution-Abatement.

Rowe, D. B., Kolp, M. R. S.E. Greer, and K.L. Getter. 2014. *Comparison of irrigation efficiency and plant health of overhead, drip, and sub-irrigation for extensive green roofs*. Ecological Engineering 64:306-313. N.p.: n.p.

Stancills Inc. 2008. "Superior Aggregate Materials for Sport and Industry." .Accessed February 24, 2015. http://stancills.com/.

Starry, O., and Gaches, W. N. 2012. Interview. College Park, MD. October 2012.

Thurston, H. W., Taylor, M. A., Roy, A., Morrison, M., Shuster, W. D., Templeton, J., Clagett, M., and Cabezas, H. 2008. "Applying a Reverse Auction to Reduce Stormwater Runoff." AMBIO: A Journal of the Human Environment 37(4): 326-327. doi: 10.1579/0044-7447(2008)37[326:AARATR]2.0.CO;2

TipthePlanet. 2012. "Green Roof." TipthePlanet. Accessed November 28, 2012. http://www.tiptheplanet.com/wiki/Green_roof.

United States Environmental Protection Agency. 2013. "Basic Information: What is an Urban Heat Island?" EPA. Accessed March 23, 2015. http://www.epa.gov/heatisland/about/index.htm.

VanWoert, N. D., Rowe, D. B., Andresen, J. A., and Rugh, C. L. 2005. "Green Roof Stormwater Retention: Effects of Roof Surface, Slope, and Media Depth." *Journal of Environmental Quality* 34, no. 3: 1036-44. Accessed September 1, 2012. http://search.proquest.com/docview/197411456?accountid=14696.

VanWoert, N. D., Rowe, D. B., Andresen, J. A., Rugh, C. L., and Xiao, L. "Watering Regime and Green Roof Substrate Design Affect Sedum Plant Growth." *HortScience* 40, no. 3 (2005): 659-64. Accessed August 29, 2012. http://hortsci.ashspublications.org/content/40/3/659.full.pdf+html.

Vernon, J., Essex, S., Pinder, D., and Curry, K. 2003. "The 'greening' of Tourism Micro-businesses: Outcomes of Focus Group Investigations in South East Cornwall." Business Strategy and the Environment 12 (1): 49–69. doi:10.1002/bse.348.

White, E. V., and Gatersleben, B. 2011. "Greenery on Residential Buildings: Does It Affect Preferences and Perceptions of Beauty?" *Journal of Environmental Psychology* 31, no. 1: 89-98. Accessed August 30, 2012. http://dx.doi.org/10.1016/j.jenvp.2010.11.002.

Wong, G. K. L., and Jim, C. Y. 2014. "Quantitative Hydrologic Performance of Extensive Green Roof under Humid-tropical Rainfall Regime." *Ecological Engineering* 70: 366-78.

Appendix A - Runoff Delay Data

Table A10. Runoff Delay Data

Rain Event (Date)	Total Prec. (mm)	Size Class.	Intensity (mm/hour)	Intensity Class.	2 deg Delay (minutes)	15 deg Delay (minutes)	30 deg Delay (minutes)	45 deg delay (minutes)
6/3/2014	16	medium	27.43	high	10	0	30	50
6/4/2014	7.8	small	4.5	low	95	55	85	55
6/8/2014	9.2	small	5.02	low	no runoff	185	215	185
6/10/2014	5	small	3.4	low	145	95	95	45
6/11/2014	5.4	small	2.82	low	140	80	100	140
6/13/2014	14.6	medium	18.67	high	15	15	15	15
6/19/2014	2	small	12	mid	130	1270	no runoff	no runoff
6/21/2014	1.2	small	4	low	no runoff	no runoff	no runoff	no runoff
6/25/2014	6	small	10.3	mid	1100	20	40	30
7/2/2014	5	small	7.2	low	950	1030	no runoff	no runoff
7/3/2014	10.6	small	5.45	low	0	575	605	595
7/8/2014	10	small	9	mid	no runoff	20	100	10
7/10/2014	1.8	small	1.92	low	1230	1270	no runoff	no runoff
7/13/2014	5.8	small	5.67	low	975	975	no runoff	no runoff
7/14/2014	4.8	small	14.4	high	0	0	15	0
7/15/2014	36.8	medium	29.24	high	10	0	0	0
7/24/2014	0.4	small	0.4	low	no runoff	no runoff	no runoff	no runoff
7/27/2014 - a	1	small	1.2	low	635	no runoff	no runoff	no runoff
7/27/2014 - b	4	small	4.8	low	960	no runoff	no runoff	no runoff
8/2/2014	3.8	small	1.06	low	835	no runoff	no runoff	no runoff
8/3/2014 - a	0.8	small	4.8	low	815	no runoff	no runoff	no runoff
8/3/2014 - b	1.8	small	2.88	low	845	no runoff	no runoff	no runoff
8/6/2014	0.8	small	3.2	low	1020	no runoff	no runoff	no runoff
8/11/2014	57.2	medium	10.7	mid	735	no runoff	845	835
8/20/2014	6	small	2.4	low	925	no runoff	no runoff	no runoff
8/22/2014	1	small	0.923	low	970	no runoff	no runoff	no runoff
8/23/2014	12.6	medium	7.9	mid	no runoff	no runoff	420	460
8/31/2014	23	medium	15.9	high	0	no runoff	15	5
9/2/2014	5	small	9.6	mid	80	no runoff	no runoff	no runoff
9/6/2014	20.2	medium	32.2	high	10	no runoff	10	20
9/11/2014	0.8	small	9.6	mid	no runoff	no runoff	590	no runoff
9/13/2014	4	small	1.17073171	low	no runoff	no runoff	no runoff	no runoff
9/25/2014	24	medium	3.31428571	low	185	475	175	375
9/30/2014	1.6	small	2.8	low	no runoff	no runoff	no runoff	OFFLINE
10/2/2014	0.2	small	2.4	low	no runoff	no runoff	no runoff	OFFLINE
10/3/2014	4.4	small	1.09090909	low	no runoff	no runoff	no runoff	OFFLINE
10/7/2014	5.6	small	5.52	low	no runoff	no runoff	no runoff	OFFLINE
10/10/2014	11.4	small	0.912	low	610	no runoff	no runoff	OFFLINE
10/13/2014	2.4	small	4.8	low	150	no runoff	no runoff	OFFLINE
10/15/2014 - a	0.2	small	2.4	low	no runoff	no runoff	no runoff	OFFLINE
10/15/2014 - b	30.8	medium	21.84	high	10	no runoff	no runoff	OFFLINE
10/16/2014	0.2	small	2.4	low	no runoff	no runoff	no runoff	OFFLINE
10/21/2014 - a	0.2	small	2.4	low	no runoff	no runoff	no runoff	OFFLINE
10/21/2014 - b	34	medium	7.2	low	315	no runoff	no runoff	OFFLINE
10/29/2014	0.6	small	0.65454545	low	no runoff	no runoff	no runoff	OFFLINE
10/30/2014	0.2	small	2.4	low	no runoff	no runoff	no runoff	OFFLINE
11/5/2014	10	small	1.05263158	low	no runoff	no runoff	345	OFFLINE
11/6/2014	5.4	small	7.8	mid	no runoff	no runoff	no runoff	OFFLINE
11/13/2014	1.2	small	0.62608696	low	no runoff	no runoff	no runoff	OFFLINE
11/16/2014	1.2	small	1.30909091	low	no runoff	no runoff	no runoff	OFFLINE
11/17/2014	23.2	medium	4.60540541	low	555	285	325	OFFLINE
11/23/2015	8.2	small	3.49090909	low	155	185	125	OFFLINE
11/26/2014	32	medium	2.35471698	low	90	80	80	OFFLINE

Appendix B - Volumetric Water Content Data

Table B1. 2^o Module Small Events

Date	Port 1 (%/100)				Port 2 (%/100)				Port 3 (%/100)				Port 4 (%/100)			
	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours
(6/4)	1	1	1	1	1	1	1	1	0.889	1	0.981	0.861	0.129	0.13	0.129	0.127
(6/8)	1	1	1	1	0.864	0.882	0.874	0.803	0.319	0.319	0.317	0.292	0.107	0.106	0.106	0.101
(6/10)	1	1	1	1	0.947	0.963	0.922	0.88	0.336	0.38	0.363	0.336	0.108	0.112	0.109	0.105
(6/11)	1	1	1	1	0.949	0.95	0.937	0.93	0.363	0.363	0.354	0.351	0.111	0.11	0.108	0.108
(6/19)	0.582	0.634	0.632	0.628	0.266	0.282	0.273	0.268	0.067	0.072	0.07	0.069	0.069	0.065	0.064	0.064
(6/21)	0.409	0.408	0.399	0.383	0.189	0.188	0.183	0.174	0.048	0.048	0.048	0.046	0.066	0.065	0.066	0.066
(6/25)	0.184	0.283	0.287	0.283	0.047	0.138	0.141	0.139	0.041	0.041	0.043	0.045	0.07	0.069	0.07	0.07
(7/2)	0.072	0.072	0.073	0.073	0.057	0.055	0.058	0.061	0.04	0.04	0.041	0.042	0.043	0.043	0.043	0.043
(7/3)	0.672	0.695	0.714	0.612	0.277	0.278	0.275	0.267	0.111	0.111	0.108	0.09	0.043	0.036	0.04	0.041
(7/8)	0.602	0.642	0.535	0.473	0.234	0.236	0.225	0.203	0.087	0.087	0.076	0.069	0.039	0.039	0.04	0.039
(7/10)	0.391	0.397	0.399	0.397	0.161	0.163	0.162	0.162	0.059	0.06	0.06	0.06	0.04	0.04	0.04	0.041
(7/13)	0.207	0.218	0.231	0.222	0.082	0.085	0.096	0.099	0.046	0.047	0.05	0.053	0.042	0.042	0.042	0.043
(7/14)	0.222	0.339	0.412	0.411	0.106	0.201	0.2	0.198	0.051	0.078	0.081	0.079	0.042	0.033	0.035	0.036
(7/24)	0.304	0.305	0.3	0.272	0.096	0.095	0.093	0.082	0.046	0.046	0.046	0.046	0.041	0.042	0.041	0.041
(7/27)a	0.069	0.067	0.067	0.066	0.048	0.047	0.049	0.049	0.042	0.041	0.043	0.042	0.037	0.037	0.039	0.036
(7/27)b	0.064	0.07	0.09	0.086	0.047	0.047	0.047	0.051	0.042	0.042	0.041	0.042	0.037	0.037	0.037	0.039
(8/2)	0.059	0.058	0.059	0.06	0.043	0.042	0.043	0.045	0.04	0.04	0.04	0.041	0.036	0.036	0.036	0.036
(8/3)	0.058	0.058	0.058	0.06	0.043	0.043	0.044	0.046	0.04	0.04	0.04	0.042	0.036	0.036	0.036	0.037
(8/3)b	0.058	0.057	0.058	0.06	0.043	0.042	0.044	0.048	0.04	0.04	0.04	0.042	0.036	0.036	0.037	0.037
(8/6)	0.057	0.057	0.055	0.058	0.045	0.045	0.043	0.046	0.041	0.04	0.04	0.042	0.037	0.037	0.037	0.038
(8/20)	0.792	0.695	0.69	0.683	0.249	0.228	0.224	0.221	0.07	0.06	0.06	0.058	0.038	0.036	0.037	0.036
(8/22)	0.661	0.679	0.674	0.67	0.223	0.229	0.224	0.221	0.058	0.059	0.058	0.058	0.037	0.037	0.036	0.036
(9/2)	1	1	1	1	0.919	0.93	0.922	0.92	0.361	0.385	0.381	0.382	0.036	0.028	0.028	0.028
(9/11)	0.96	0.973	0.979	0.987	0.58	0.602	0.603	0.597	0.228	0.235	0.229	0.225	0.036	0.035	0.035	0.035
(9/13)	1	1	1	1	0.57	0.616	0.618	0.618	0.219	0.228	0.215	0.213	0.036	0.034	0.034	0.034
(9/30)	0.872	0.879	0.887	0.882	0.418	0.42	0.423	0.43	0.132	0.132	0.132	0.132	0.036	0.036	0.036	0.036
(10/2)	0.825	0.824	0.814	0.802	0.376	0.376	0.373	0.362	0.113	0.113	0.112	0.106	0.036	0.036	0.037	0.036
(10/3)	0.938	0.941	0.946	0.917	0.445	0.451	0.452	0.427	0.142	0.142	0.139	0.132	0.036	0.035	0.035	0.036
(10/7)	0.826	0.902	0.931	0.943	0.371	0.418	0.42	0.418	0.117	0.139	0.137	0.136	0.036	0.028	0.029	0.031
(10/10)	1	1	1	1	0.714	0.75	0.696	0.692	0.243	0.242	0.24	0.238	0.036	0.03	0.03	0.03
(10/13)	1	1	1	1	0.7	0.704	0.69	0.685	0.238	0.241	0.238	0.237	0.03	0.03	0.03	0.03
(10/15)	0.975	0.982	0.975	1	0.622	0.627	0.621	1	0.209	0.21	0.208	1	0.029	0.029	0.03	0.031
(10/16)	1	1	1	1	1	1	1	1	1	1	1	1	0.031	0.031	0.031	0.031
(10/21)	0.999	1	1	0.983	0.78	0.781	0.783	0.765	0.271	0.273	0.27	0.27	0.034	0.034	0.034	0.035
(10/29)	0.915	0.915	0.916	0.906	0.537	0.531	0.532	0.493	0.169	0.166	0.166	0.162	0.034	0.034	0.034	0.033
(10/30)	0.914	0.915	0.916	0.906	0.53	0.531	0.532	0.493	0.166	0.166	0.166	0.162	0.034	0.034	0.034	0.033
(11/5)	1	1	1	1	0.742	0.742	0.742	0.741	0.238	0.229	0.225	0.223	0.034	0.027	0.027	0.027
(11/6)	1	1	1	1	0.742	0.742	0.742	0.741	0.238	0.229	0.225	0.223	0.028	0.027	0.027	0.027
(11/13)	0.917	0.926	0.945	0.944	0.51	0.519	0.531	0.524	0.125	0.127	0.13	0.127	0.034	0.034	0.034	0.033
(11/16)	1	1	1	1	1	1	1	1	1	1	1	1	0.034	0.028	0.028	0.031
(11/23)	1	1	1	1	1	1	1	1	1	1	1	1	0.029	0.028	0.028	0.028
AVG	0.673	0.6827	0.68395	0.6772439	0.453	0.4629	0.45944	0.4609512	0.222	0.2271	0.22471	0.2383902	0.046	0.0444	0.04461	0.0445122

Table B2. 2º Module Medium Events

	Port 1 (%/100)				Port 2 (%/100)				Port 3 (%/100)				Port 4 (%/100)			
Date	**Peak**	**1 hours**	**6 Hours**	**12 hours**	**Peak**	**1 Hour**	**6 hours**	**12 hours**	**Peak**	**1 Hour**	**6 hours**	**12 hours**	**Peak**	**1 hour**	**6 hours**	**12 hours**
(6/3)	1	1	1	1	0	1	1	1	0	1	1	0.88	0	0.137	0.136	0.13
(6/13)	1	1	1	1	0	1	1	1	0	1	1	1	0	0.129	0.123	0.123
(7/15)	1	1	1	1	0	1	1	1	0	1	1	1	0	0.041	0.034	0.034
(8/11)	1	1	1	1	0	1	1	1	0	1	1	1	0	0.034	0.027	0.027
(8/23)	1	1	1	1	0	0.481	0.537	0.538	0	0.213	0.214	0.209	0	0.037	0.028	0.029
(8/31)	1	1	1	1	0	1	0.995	0.999	0	0.514	0.511	0.497	0	0.037	0.031	0.031
(9/6)	1	1	1	1	0	1	1	1	0	0.489	1	1	0	0.036	0.03	0.03
(9/25)	1	1	1	1	0	0.699	0.691	0.674	0	0.273	0.267	0.261	0	0.038	0.031	0.03
(10/15)b	1	1	1	1	0	1	1	1	0	1	1	1	0	0.031	0.031	0.031
(10/21)b	1	1	1	1	0	1	1	1	0	1	1	1	0	0.034	0.031	0.03
(11/17)	1	1	1	1	0	1	1	1	0	1	1	1	0	0.034	0.028	0.028
(11/26)	1	1	1	1	0	1	1	1	0	1	1	1	0	0.028	0.028	0.028
AVG	1	1	1	1	0	0.9317	0.93525	0.93425	0	0.7908	0.83267	0.8205833	0	0.0513	0.0465	0.0459167

Table B3. 15º Module Small Events

	Port 1 (%/100)				Port 2 (%/100)				Port 3 (%/100)				Port 4 (%/100)			
Date	**Peak**	**1 Hour**	**6 Hours**	**12 Hours**	**Peak**	**1 Hour**	**6 Hours**	**12 Hours**	**Peak**	**1 Hour**	**6 Hours**	**12 Hours**	**Peak**	**1 Hour**	**6 Hours**	**12 Hours**
(6/4)	0.126	0.128	0.124	0.121	0.147	0.147	0.151	0.152	0.086	0.085	0.085	0.085	0.03	0.029	0.029	0.029
(6/8)	0.123	0.121	0.118	0.109	0.147	0.147	0.148	0.148	0.094	0.091	0.895	0.088	0.027	0.033	0.031	0.029
(6/10)	0.114	0.127	0.119	0.111	0.148	0.147	0.15	0.148	0.087	0.085	0.085	0.084	0.033	0.031	0.031	0.03
(6/11)	0.121	0.118	0.116	0.114	0.15	0.15	0.149	0.148	0.084	0.084	0.084	0.083	0.034	0.033	0.032	0.031
(6/19)									0.079	0.078	0.078	0.078	0.03	0.03	0.029	0.027
(6/21)	0.082	0.081	0.081	0.08	0.147	0.147	0.147	0.147	0.097	0.094	0.091	0.089	0.031	0.031	0.03	0.029
(6/25)	0.074	0.074	0.074	0.075	0.15	0.15	0.149	0.15	0.095	0.092	0.091	0.09	0.03	0.03	0.03	0.029
(7/2)	0.063	0.063	0.064	0.064	0.148	0.148	0.148	0.148	0.1	0.09	0.089	0.088	0.03	0.03	0.031	0.033
(7/3)	0.097	0.094	0.091	0.091	0.153	0.153	0.152	0.151	0.085	0.084	0.083	0.082	0.034	0.032	0.031	0.031
(7/8)	0.105	0.097	0.087	0.079	0.198	0.148	0.129	0.115	0.085	0.083	0.082	0.082	0.037	0.034	0.034	0.034
(7/10)																
(7/13)	0.078	0.078	0.078	0.078	0.103	0.101	0.099	0.098	0.082	0.081	0.08	0.08	0.035	0.028	0.028	0.028
(7/14)	0.076	0.074	0.074	0.076	0.091	0.09	0.09	0.091	0.081	0.079	0.079	0.079	0.028	0.026	0.026	0.027
(7/24)	0.148	0.148	0.141	0.135	0.221	0.218	0.181	0.151	0.076	0.076	0.076	0.075	0.027	0.025	0.025	0.026
(7/27)a	0.075	0.075	0.074	0.074	0.09	0.09	0.089	0.09	0.076	0.075	0.025	0.075	0.025	0.025	0.024	0.025
(7/27)b	0.07	0.069	0.07	0.069	0.087	0.087	0.087	0.086	0.075	0.074	0.073	0.073	0.026	0.024	0.024	0.025
(8/2)	0.068	0.067	0.066	0.068	0.086	0.086	0.085	0.087	0.073	0.072	0.076	0.076	0.025	0.024	0.024	0.025
(8/3)a	0.061	0.06	0.061	0.062	0.091	0.091	0.091	0.091	0.076	0.076	0.076	0.075	0.024	0.024	0.024	0.025
(8/3)b	0.061	0.06	0.061	0.063	0.093	0.093	0.094	0.096	0.075	0.074	0.073	0.073	0.026	0.026	0.025	0.025
(8/6)	0.062	0.062	0.061	0.06	0.093	0.094	0.093	0.093	0.074	0.073	0.073	0.073	0.03	0.029	0.028	0.027
(8/20)	0.058	0.056	0.056	0.055	0.085	0.083	0.083	0.082	0.073	0.072	0.072	0.072	0.026	0.025	0.024	0.025
(8/22)	0.057	0.056	0.056	0.055	0.084	0.083	0.083	0.082	0.072	0.072	0.071	0.071	0.025	0.025	0.024	0.024
(9/2)	0.072	0.081	0.088	0.087	0.093	0.093	0.093	0.093	0.064	0.065	0.066	0.067	0.025	0.025	0.025	0.026
(9/11)	0.065	0.064	0.063	0.063	0.092	0.092	0.09	0.09	0.078	0.078	0.077	0.077	0.031	0.03	0.029	0.027
(9/13)	0.063	0.063	0.062	0.061	0.088	0.088	0.087	0.087	0.078	0.076	0.076	0.075	0.026	0.025	0.024	0.024
(9/30)	0.063	0.063	0.063	0.064	0.079	0.079	0.079	0.079	0.081	0.081	0.08	0.079	0.03	0.03	0.028	0.027
(10/2)	0.063	0.063	0.063	0.063	0.078	0.078	0.078	0.078	0.079	0.079	0.078	0.078	0.027	0.028	0.027	0.027
(10/3)	0.062	0.061	0.061	0.063	0.076	0.075	0.075	0.076	0.078	0.078	0.077	0.077	0.027	0.027	0.028	0.028
(10/7)	0.061	0.06	0.067	0.067	0.075	0.074	0.074	0.075	0.086	0.082	0.076	0.076	0.029	0.029	0.028	0.028
(10/10)	0.093	0.09	0.088	0.086	0.075	0.074	0.076	0.078	0.105	0.101	0.083	0.078	0.026	0.026	0.028	0.028
(10/13)	0.072	0.078	0.078	0.077	0.079	0.079	0.079	0.079	0.092	0.092	0.091	0.09	0.026	0.026	0.026	0.027
(10/15)	0.072	0.072	0.072	0.094	0.078	0.078	0.078	0.168	0.13	0.127	0.087	0.087	0.027	0.027	0.029	0.028
(10/16)	0.107	0.106	0.106	0.104	0.14	0.137	0.126	0.114	0.079	0.079	0.08	0.08	0.03	0.029	0.028	0.028
(10/21)	0.072	0.072	0.072	0.073	0.078	0.078	0.077	0.078	0.106	0.94	0.08	0.079	0.027	0.027	0.027	0.029
(10/29)	0.069	0.069	0.068	0.067	0.075	0.075	0.075	0.075	0.076	0.076	0.077	0.078	0.028	0.03	0.029	0.028
(10/30)	0.067	0.067	0.067	0.068	0.075	0.075	0.074	0.075	0.074	0.075	0.076	0.076	0.027	0.028	0.028	0.029
(11/5)	0.08	0.086	0.083	0.09	0.141	0.169	0.166	0.168	0.092	0.084	0.072	0.066	0.027	0.027	0.028	0.028
(11/6)	0.093	0.089	0.088	0.087	0.169	0.166	0.16	0.151	0.101	0.96	0.085	0.072	0.028	0.027	0.027	0.027
(11/13)	0.067	0.066	0.066	0.066	0.078	0.077	0.077	0.077	0.075	0.075	0.074	0.074	0.027	0.027	0.027	0.027
(11/16)	0.061	0.061	0.061	0.081	0.075	0.075	0.075	0.075	0.077	0.075	0.073	0.072	0.027	0.027	0.027	0.027
(11/23)	0.104	0.104	0.102	0.099	0.172	0.173	0.153	0.115	0.109	0.107	0.086	0.084	0.028	0.027	0.026	0.026
Avg	0.08	0.0801	0.07923	0.0794615	0.111	0.1099	0.10744	0.1073077	0.085	0.1255	0.09828	0.0784	0.028	0.0279	0.02758	0.027575

Table B4. 15º Module Medium Events

Date		Peak	1 Hour	6 Hours	12 Hours		Peak	1 Hour	6 Hours	12 Hours		Peak	1 Hour	6 Hours	12 Hours		Peak	1 Hour	6 Hours	12 Hours
(6/3)		0.109	0.119	0.112	0.111		0.147	0.163	0.15	0.145		0.089	0.088	0.086	0.085		0.027	0.027	0.026	0.026
(6/13)		0.129	0.121	0.121	0.121		0.154	0.153	0.153	0.152		0.096	0.093	0.091	0.088		0.03	0.031	0.03	0.03
(7/15)		0.074	0.073	0.075	0.076		0.09	0.09	0.091	0.081		0.078	0.078	0.077	0.076		0.029	0.025	0.025	0.026
(8/11)		0.072	0.07	0.096	0.092		0.09	0.179	0.136	0.118		0.074	0.073	0.072	0.072		0.03	0.026	0.025	0.027
(8/23)		0.099	0.096	0.09	0.086		0.082	0.082	0.082	0.086		0.07	0.07	0.069	0.069		0.025	0.025	0.024	0.024
(8/31)		0.096	0.094	0.09	0.088		0.096	0.096	0.102	0.1		0.067	0.061	0.06	0.061		0.025	0.025	0.024	0.025
(9/6)		0.091	0.089	0.085	0.082		0.09	0.09	0.097	0.102		0.087	0.083	0.081	0.079		0.026	0.026	0.027	0.025
(9/25)		0.093	0.091	0.09	0.087		0.082	0.084	0.089	0.088		0.111	0.12	0.117	0.113		0.024	0.024	0.025	0.027
(10/15)		0.112	0.112	0.109	0.106		0.182	0.183	0.161	0.134		0.109	0.114	0.116	0.117		0.026	0.026	0.026	0.027
(10/21)		0.109	0.109	0.106	0.105		0.188	0.188	0.16	0.127		0.076	0.076	0.077	0.078		0.028	0.03	0.029	0.028
(11/17)		0.111	0.109	0.106	0.102		0.192	0.18	0.144	0.118		0.115	0.109	0.082	0.077		0.028	0.028	0.027	0.027
(11/26)		0.105	0.108	0.116	0.115		0.184	0.195	0.193	0.192		0.153	0.142	0.094	0.083		0.026	0.027	0.027	0.027
Avg		0.1	0.0993	0.09967	0.0975833		0.131	0.1403	0.12983	0.12025		0.094	0.0923	0.08517	0.0831667		0.027	0.0267	0.02625	0.0265833

Table B5. 30º Module Small Events

Date	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours
(6/4)	0.037	0.039	0.039	0.039	0.046	0.045	0.048	0.043	0.027	0.025	0.025	0.026	0.028	0.028	0.028	0.029
(6/8)	0.038	0.038	0.039	0.039	0.037	0.049	0.049	0.046	0.028	0.025	0.027	0.028	0.03	0.03	0.03	0.031
(6/10)	0.037	0.039	0.039	0.038	0.04	0.04	0.048	0.043	0.027	0.025	0.027	0.026	0.03	0.03	0.031	0.03
(6/11)	0.039	0.038	0.038	0.038	0.042	0.041	0.04	0.04	0.027	0.025	0.025	0.025	0.028	0.028	0.027	0.028
(6/19)	0.037	0.036	0.036	0.036	0.039	0.037	0.036	0.036	0.027	0.027	0.026	0.026	0.028	0.028	0.028	
(6/21)	0.034	0.034	0.034	0.034	0.036	0.035	0.036	0.035	0.026	0.026	0.026	0.026	0.027	0.027	0.028	0.027
(6/25)	0.028	0.027	0.027	0.028	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.028	0.028	0.027	0.028
(7/2)	0.026	0.026	0.027	0.027	0.025	0.025	0.025	0.026	0.026	0.025	0.026	0.027	0.027	0.027	0.028	0.027
(7/3)	0.028	0.027	0.027	0.027	0.027	0.026	0.026	0.027	0.027	0.026	0.026	0.027	0.028	0.028	0.027	0.028
(7/8)	0.028	0.028	0.028	0.027	0.027	0.027	0.027	0.025	0.027	0.027	0.028	0.027	0.028	0.028	0.028	0.027
(7/10)	0.028	0.027	0.027	0.028	0.027	0.026	0.026	0.026	0.027	0.027	0.027	0.027	0.028	0.027	0.027	0.027
(7/13)	0.028	0.028	0.028	0.03	0.027	0.027	0.027	0.028	0.027	0.027	0.027	0.028	0.028	0.027	0.027	0.029
(7/14)	0.029	0.029	0.028	0.028	0.029	0.028	0.027	0.027	0.028	0.027	0.027	0.027	0.028	0.028	0.028	0.028
(7/24)	0.027	0.027	0.027	0.027	0.04	0.039	0.039	0.034	0.025	0.025	0.025	0.026	0.027	0.027	0.027	0.027
(7/27)a	0.026	0.026	0.027	0.026	0.024	0.024	0.024	0.024	0.025	0.025	0.026	0.025	0.027	0.027	0.027	0.027
(7/27)b	0.026	0.027	0.026	0.027	0.024	0.025	0.025	0.026	0.025	0.025	0.025	0.026	0.027	0.027	0.027	0.028
(8/2)	0.025	0.025	0.026	0.027	0.024	0.024	0.024	0.025	0.025	0.025	0.025	0.027	0.027	0.027	0.027	0.028
(8/3)a	0.026	0.026	0.026	0.027	0.024	0.024	0.025	0.026	0.025	0.025	0.025	0.027	0.027	0.027	0.027	0.028
(8/3)b	0.026	0.026	0.027	0.028	0.025	0.025	0.025	0.027	0.026	0.025	0.027	0.028	0.028	0.027	0.028	0.03
(8/6)	0.025	0.025	0.025	0.026	0.024	0.024	0.024	0.025	0.025	0.025	0.025	0.027	0.028	0.028	0.028	0.03
(8/20)	0.029	0.027	0.027	0.027	0.028	0.026	0.026	0.025	0.028	0.027	0.026	0.026	0.03	0.028	0.028	0.028
(8/22)	0.027	0.027	0.027	0.027	0.027	0.027	0.026	0.026	0.027	0.027	0.026	0.026	0.028	0.028	0.028	0.028
(9/2)	0.028	0.028	0.028	0.028	0.027	0.027	0.027	0.027	0.028	0.027	0.027	0.027	0.028	0.028	0.028	0.028
(9/11)	0.03	0.029	0.028	0.027	0.03	0.029	0.027	0.027	0.031	0.03	0.03	0.029	0.03	0.029	0.028	0.028
(9/13)	0.028	0.028	0.028	0.028	0.028	0.028	0.027	0.027	0.03	0.03	0.029	0.029	0.03	0.029	0.029	0.028
(9/30)	0.028	0.028	0.028	0.028	0.03	0.03	0.03	0.03	0.028	0.028	0.028	0.028	0.031	0.031	0.031	0.031
(10/2)	0.028	0.028	0.03	0.03	0.029	0.029	0.031	0.031	0.027	0.027	0.027	0.028	0.031	0.031	0.033	0.033
(10/3)	0.03	0.029	0.028	0.029	0.031	0.031	0.031	0.031	0.027	0.027	0.027	0.027	0.033	0.032	0.033	0.033
(10/7)	0.03	0.029	0.029	0.03	0.032	0.032	0.031	0.032	0.03	0.027	0.027	0.028	0.035	0.034	0.034	0.035
(10/10)	0.029	0.028	0.028	0.028	0.032	0.031	0.031	0.031	0.028	0.027	0.027	0.027	0.034	0.033	0.034	0.034
(10/13)	0.029	0.029	0.03	0.029	0.032	0.032	0.032	0.032	0.028	0.028	0.028	0.028	0.035	0.034	0.035	0.034
(10/15)a	0.03	0.03	0.03	0.029	0.032	0.032	0.032	0.031	0.029	0.028	0.029	0.027	0.036	0.036	0.036	0.033
(10/16)	0.029	0.029	0.029	0.03	0.031	0.031	0.031	0.032	0.027	0.027	0.027	0.027	0.033	0.033	0.034	0.034
(10/21)a	0.029	0.029	0.028	0.031	0.033	0.033	0.032	0.036	0.029	0.029	0.028	0.03	0.036	0.036	0.036	0.038
(10/29)	0.03	0.029	0.029	0.028	0.039	0.039	0.037	0.037	0.031	0.03	0.03	0.03	0.039	0.039	0.038	0.038
(10/30)	0.028	0.028	0.028	0.03	0.037	0.037	0.037	0.039	0.03	0.03	0.03	0.031	0.038	0.038	0.038	0.04
(11/5)	0.029	0.028	0.029	0.028	0.039	0.037	0.04	0.039	0.03	0.027	0.028	0.027	0.037	0.037	0.037	0.037
(11/6)	0.03	0.028	0.027	0.027	0.04	0.039	0.039	0.038	0.028	0.027	0.027	0.027	0.037	0.037	0.036	0.035
(11/13)	0.028	0.027	0.027	0.027	0.04	0.04	0.04	0.039	0.029	0.029	0.029	0.029	0.039	0.037	0.038	0.038
(11/16)	0.028	0.028	0.028	0.028	0.042	0.042	0.042	0.043	0.03	0.03	0.03	0.028	0.04	0.039	0.039	0.039
(11/23)	0.029	0.029	0.029	0.029	0.043	0.043	0.045	0.045	0.03	0.03	0.029	0.03	0.041	0.041	0.04	0.04
Avg	0.03	0.029	0.0292	0.02939	0.03	0.032	0.0322	0.03202	0.03	0.027	0.0271	0.02734	0.03	0.031	0.0309	0.03123

Table B6. 30º Module Medium Events

Date	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours
(6/3)	0.039	0.04	0.039	0.038	0.048	0.045	0.045	0.045	0.028	0.025	0.025	0.025	0.028	0.028	0.028	0.027
(6/13)	0.045	0.041	0.04	0.04	0.043	0.043	0.042	0.042	0.027	0.025	0.024	0.024	0.029	0.028	0.028	0.028
(7/15)	0.03	0.028	0.028	0.028	0.194	0.17	0.135	0.11	0.028	0.026	0.025	0.026	0.029	0.027	0.028	0.028
(8/11)	0.027	0.025	0.026	0.026	0.026	0.026	0.026	0.026	0.025	0.025	0.025	0.025	0.027	0.027	0.027	0.027
(8/23)	0.028	0.026	0.027	0.027	0.028	0.026	0.026	0.027	0.027	0.026	0.026	0.025	0.028	0.028	0.028	0.028
(8/31)	0.027	0.026	0.027	0.028	0.027	0.025	0.026	0.027	0.026	0.022	0.026	0.026	0.028	0.027	0.027	0.028
(9/6)	0.029	0.027	0.027	0.027	0.028	0.027	0.027	0.027	0.03	0.028	0.028	0.028	0.03	0.029	0.029	0.028
(9/25)	0.028	0.027	0.028	0.028	0.027	0.027	0.027	0.027	0.027	0.025	0.027	0.027	0.028	0.028	0.029	0.029
(10/15)b	0.031	0.031	0.029	0.029	0.033	0.031	0.031	0.031	0.029	0.027	0.027	0.027	0.036	0.032	0.033	0.033
(10/21)b	0.03	0.03	0.029	0.028	0.036	0.034	0.034	0.034	0.03	0.028	0.028	0.027	0.037	0.034	0.036	0.036
(11/17)	0.029	0.028	0.027	0.027	0.043	0.042	0.042	0.042	0.03	0.028	0.027	0.028	0.039	0.039	0.038	0.039
(11/26)	0.029	0.028	0.027	0.027	0.04	0.04	0.039	0.04	0.03	0.028	0.028	0.028	0.04	0.04	0.04	0.04
Avg	0.031	0.0298	0.0295	0.0294167	0.048	0.0447	0.04167	0.0398333	0.028	0.0261	0.02633	0.0263333	0.032	0.0306	0.03092	0.0309167

Table B7. 45º Module Small Events

Date	Peak	1 hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours
(6/4)	0.215	0.2078	0.2156	0.218	0.058	0.0578	0.0746	0.0722	0.055	0.1028	0.0824	0.0746	0.025	0.0248	0.0248	0.0254
(6/8)	0.206	0.2138	0.2252	0.206	0.126	0.1256	0.1046	0.0782	0.09	0.0836	0.0728	0.065	0.024	0.0236	0.0242	0.0236
(6/10)	0.193	0.1904	0.1952	0.191	0.061	0.0602	0.0722	0.071	0.061	0.095	0.0716	0.0644	0.024	0.0242	0.0242	0.0236
(6/11)	0.184	0.1808	0.179	0.1766	0.064	0.0608	0.0596	0.059	0.057	0.0554	0.0548	0.0542	0.024	0.0236	0.0236	0.0236
(6/19)	0.13	0.13	0.127	0.126	0.043	0.042	0.04	0.04	0.038	0.037	0.037	0.036	0.022	0.022	0.022	0.022
(6/21)	0.11	0.1082	0.1058	0.104	0.034	0.0332	0.0326	0.032	0.033	0.032	0.0314	0.0302	0.022	0.0218	0.0218	0.0218
(6/25)	0.03	0.0296	0.0296	0.0296	0.025	0.0248	0.0248	0.0242	0.025	0.0248	0.0248	0.0242	0.022	0.0224	0.023	0.023
(7/2)	0.028	0.0278	0.0278	0.0278	0.024	0.0236	0.0236	0.0242	0.024	0.0242	0.0236	0.023	0.022	0.0224	0.023	0.0224
(7/3)	0.033	0.032	0.0314	0.0314	0.025	0.0254	0.0248	0.0242	0.03	0.0482	0.0548	0.053	0.023	0.023	0.023	0.0224
(7/8)	0.031	0.0314	0.0338	0.0314	0.025	0.0254	0.0248	0.0242	0.024	0.0242	0.0236	0.0242	0.023	0.023	0.0224	0.0224
(7/10)	0.033	0.032	0.0314	0.0302	0.025	0.0248	0.0248	0.0248	0.024	0.0242	0.0242	0.0248	0.022	0.0224	0.0218	0.0218
(7/13)	0.03	0.0302	0.0302	0.0314	0.024	0.0242	0.0242	0.0248	0.024	0.0242	0.0242	0.0248	0.022	0.0218	0.0224	0.023
(7/14)	0.034	0.035	0.0338	0.0338	0.025	0.0254	0.0254	0.0254	0.025	0.0248	0.0254	0.0254	0.025	0.0248	0.0254	0.0254
(7/24)	0.028	0.0278	0.0278	0.0278	0.024	0.0236	0.0236	0.0236	0.024	0.0236	0.023	0.023	0.021	0.0212	0.0218	0.0218
(7/27)a	0.027	0.0266	0.0272	0.0266	0.024	0.0236	0.0236	0.0236	0.024	0.0236	0.023	0.023	0.021	0.0212	0.0218	0.0212
(7/27)b	0.028	0.0278	0.0278	0.0272	0.024	0.0242	0.0242	0.0236	0.024	0.0248	0.0242	0.0242	0.022	0.0218	0.0224	0.0224
(8/2)	0.027	0.0278	0.0278	0.0272	0.024	0.0236	0.0236	0.0236	0.024	0.0242	0.0236	0.0236	0.021	0.0212	0.0224	0.0224
(8/3/)a	0.028	0.0272	0.0278		0.024	0.0236	0.0236		0.024	0.0242	0.0242		0.022	0.0218	0.0218	
(8/3)b	0.028	0.0272	0.0272	0.0272	0.024	0.0236	0.0236	0.0236	0.024	0.023	0.0236	0.0242	0.022	0.0218	0.0212	0.0212
(8/6)	0.027	0.0266	0.0266	0.0266	0.023	0.023	0.023	0.0236	0.023	0.023	0.0236	0.023	0.021	0.0206	0.0206	0.0218
(8/20)	0.03	0.028	0.028	0.028	0.026	0.024	0.024	0.024	0.028	0.025	0.025	0.025	0.023	0.022	0.022	0.022
(8/22)	0.03	0.03	0.028	0.028	0.025	0.024	0.024	0.024	0.025	0.025	0.025	0.025	0.022	0.022	0.021	0.021
(9/2)	0.036	0.036	0.035	0.034	0.025	0.025	0.025	0.025	0.027	0.027	0.026	0.026	0.022	0.022	0.022	0.022
(9/11)	0.034	0.034	0.033	0.033	0.025	0.024	0.024	0.024	0.025	0.025	0.025	0.025	0.021	0.021	0.021	0.021
(9/13)	0.034	0.034	0.033	0.032	0.024	0.024	0.024	0.024	0.025	0.025	0.025	0.025	0.021	0.021	0.021	0.021
Avg	0.064	0.0641	0.0646	0.0647833	0.034	0.0336	0.03369	0.0327833	0.032	0.0358	0.03367	0.03295	0.022	0.0223	0.02242	0.022425

Table B8. 45º Module Medium Events

	Port 1 (%/100)				Port 2 (%/100)				Port 3 (%/100)				Port 4 (%/100)			
Date	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours	Peak	1 Hour	6 Hours	12 Hours
(6/3)	0.158	0.3098	0.2666	0.2438	0.269	0.1604	0.0818	0.0656	0.117	0.0908	0.065	0.0608	0.033	0.0308	0.0272	0.0266
(6/13)	0.258	0.2216	0.2126	0.2066	0.135	0.0932	0.086	0.0782	0.107	0.0806	0.0764	0.0728	0.024	0.0236	0.0236	0.0236
(7/15)	0.036	0.0344	0.035	0.0374	0.025	0.0248	0.0254	0.026	0.082	0.1046	0.0848	0.0698	0.024	0.0242	0.0242	0.0242
(8/11)	0.027	0.026	0.026	0.027	0.024	0.023	0.023	0.023	0.023	0.023	0.024	0.024	0.022	0.021	0.021	0.021
(8/23)	0.032	0.032	0.032	0.032	0.025	0.025	0.026	0.025	0.027	0.027	0.027	0.027	0.022	0.022	0.022	0.022
(8/31)	0.031	0.03	0.033	0.033	0.025	0.026	0.025	0.026	0.028	0.027	0.027	0.027	0.022	0.022	0.022	0.024
(9/6)	0.04	0.037	0.038	0.037	0.026	0.025	0.025	0.024	0.027	0.027	0.027	0.026	0.022	0.022	0.022	0.022
(9/25)	0.034	0.033	0.033	0.031	0.025	0.025	0.024	0.024	0.027	0.027	0.026	0.026	0.022	0.022	0.022	0.022
Avg	0.077	0.0905	0.08453	0.080975	0.069	0.0503	0.03953	0.036475	0.055	0.0509	0.04465	0.041675	0.024	0.0235	0.023	0.023175

Appendix C - Photos

Figure 32. Truss frame of 30 degree module taken in Sep. 2012 (Courtesy of Ben Borchers)


Figure 33. Overview of 15, 30, and 45 degree modules taken in Sep. 2012 (Courtesy of Ben Borchers)

Figure 34. Installing probes on 45 degree module after laying out rock wool layer. Taken in Oct. 2013 (Courtesy of Ben Borchers)

Figure 35. Overview of control, 15, and 30 degree modules after filling with substrate and planting. Taken in Oct. 2013 (Courtesy of Ben Borchers)


Figure 36. Overview of control, 15, 30, and 45 degree modules taken in Oct. 2013 (Courtesy of Ben Borchers)

Figure 37. ***Sedum hybridum*** **taken in Apr. 2014 (Courtesy of Ben Borchers)**

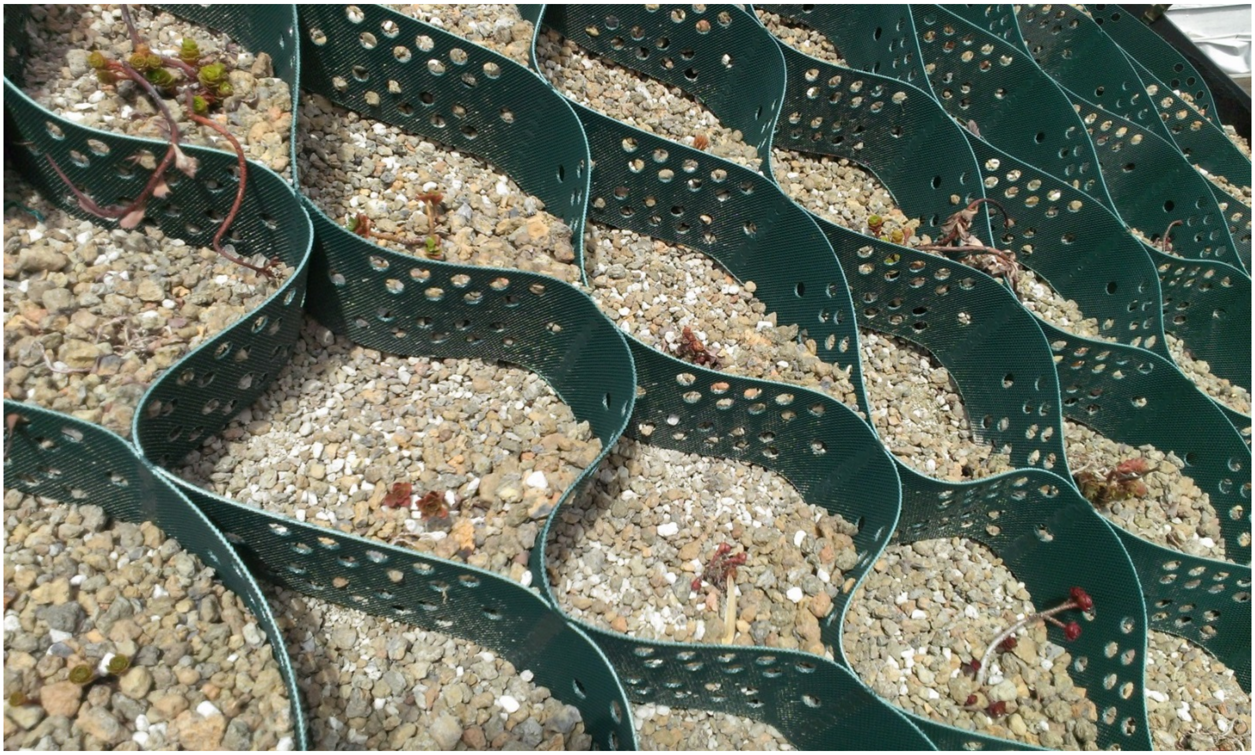

Figure 38. Close-up of different Sedum plants taken in Apr. 2014 (Courtesy of Ben Borchers)

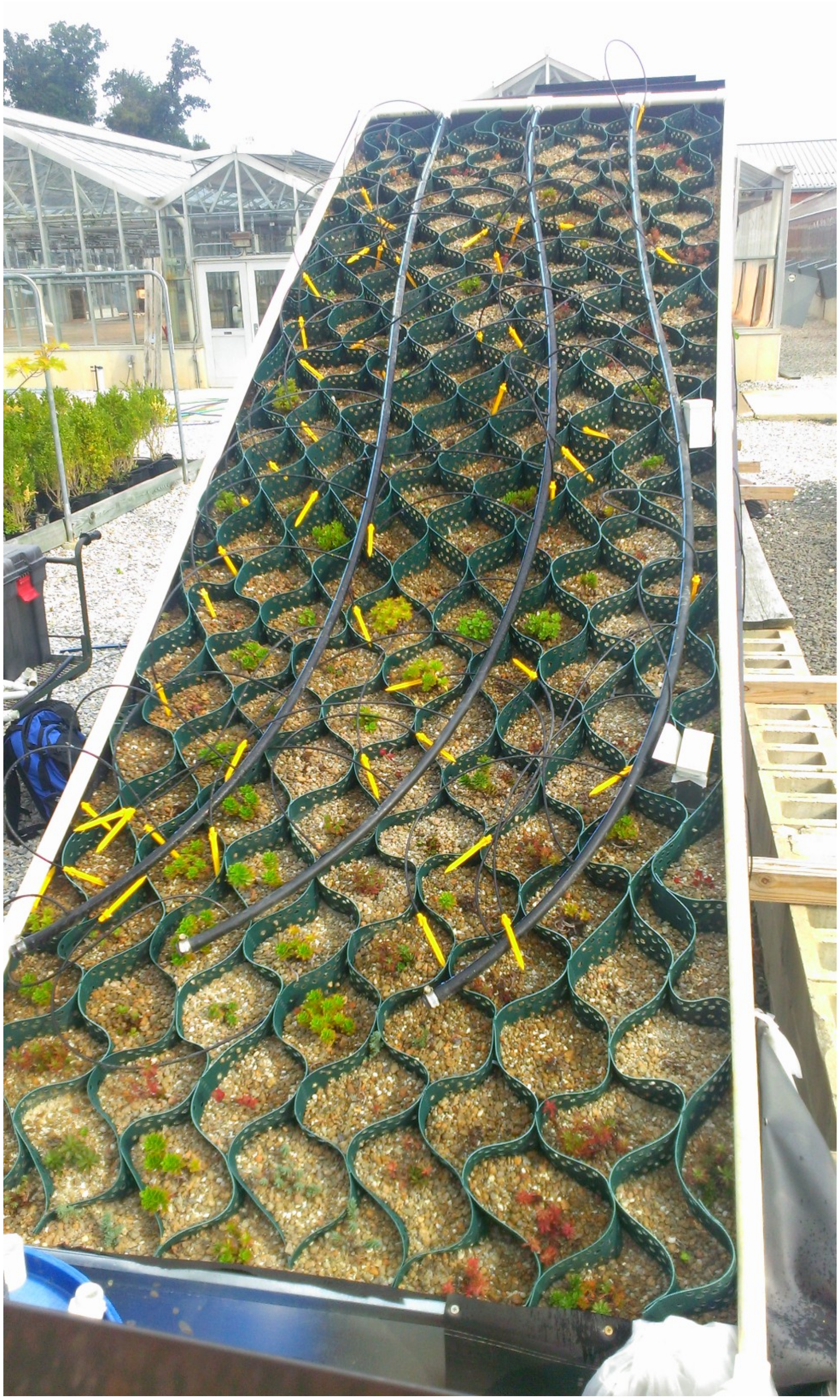

Figure 39. Irrigation system implemented on 30 degree module taken in Sep. 2014 (Courtesy of Ben Borchers)

Appendix D - Focus Group

Figure 40. Focus Group Flyer

Appendix E - Focus Group A Questions

<u>Pre Presentation Questions:</u>

- How interested are you in green home improvements? (bio retaining walls, solar panels, rain barrels, green roofs)
    - How much do you consider the environmental impact when renovating your home?
- Presentation: What do you know about green roofs? (What are they?, how they work?)

<u>Key Questions:</u>

- In how many years are you thinking of replacing your roof?
- What are the most compelling reasons that you would get a green roof?
- What do you see as the biggest drawbacks to installing a green roof?
- How much would you be willing to pay to install a green roof retrofit?
    - PG County legislation for rebates up to $2,000 to residents who install stormwater retrofit initiatives.

<u>Closing:</u>

- How interested would you be in installing a retrofitted green roof system on your home?
    - Would you rather install it yourself or have someone else do it?
- Is there anything else you would like to add?

Appendix F - Focus Group B Questions

Pre Presentation Questions:

- What was your initial reaction to the green roofs? (aesthetics)
    - Would you want it on your house? What appeals to you aesthetically? What don't you like about it? Does the slope make a difference?
    - Returners: How does this differ from what you had imagined?
    - Newbs: How does this differ from what you expected?

Post-Presentation

- How much would you be willing to pay to install the green roof retrofit? Rebate impact?
- How much maintenance would you be okay with?
- How long are you willing to wait for plants to fill out? Any problems with the winter?
- What would your neighbors think if you got our green roof? What would you think if your neighbors got one?
- What are the most compelling reasons that you would get a green roof?
- What do you see as the biggest drawbacks to installing a green roof?

Closing:

- How interested would you be in installing a retrofitted green roof system on your home?
- Is there anything else you would like to add?

Appendix G – Cost of Roof Calculations

Table 11. Cost Calculation

Materials	Cost	Per Unit
EPDM	$0.65	ft.^{2}
Flashing	$2.46	ft.
Substrate	$3.83	ft.^{3}
Plants	$2.41	ft.^{2}
Steel	$1.25	ft.^{2}
GeoCell	$0.96	ft.^{2}
Aluminum	$2.07	ft.
Filter Fabric	$0.12	ft.^{2}
Drainage Layer	$0.50	ft.^{2}
Rock Wool	$0.60	ft.^{2} per in.
Labor	$85.00	hour
Total:	$6.93	ft.^{2}
Total:	$10,397.40	Assume 1500 sq. ft. roof
Cost per sq. ft.:	**$6.9316**	60x25 ft. 170 ft. perimeter
w/ Labor	$15,072.40	Assume 55 hours labor
Cost per sq. ft.:	**$10.05**	

Appendix H – Correlation between Runoff Delay and Storm Size Plots

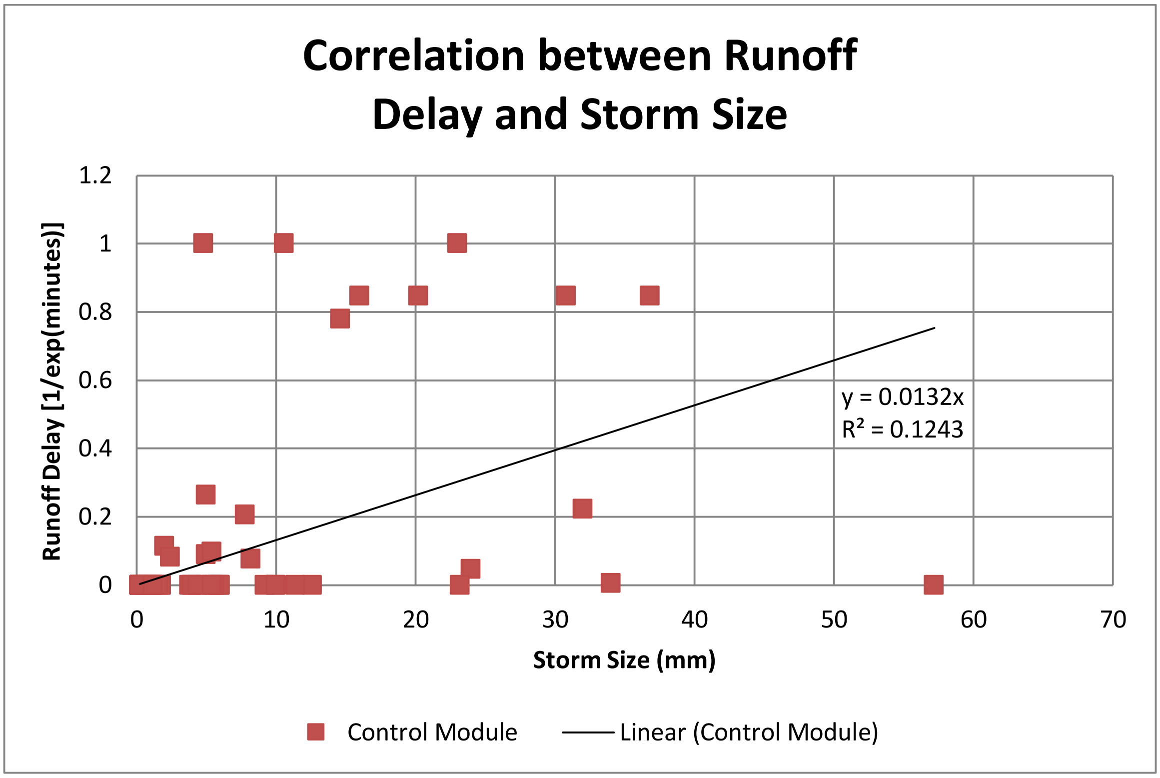

Figure 41. Correlation between Runoff Delay and Storm Size

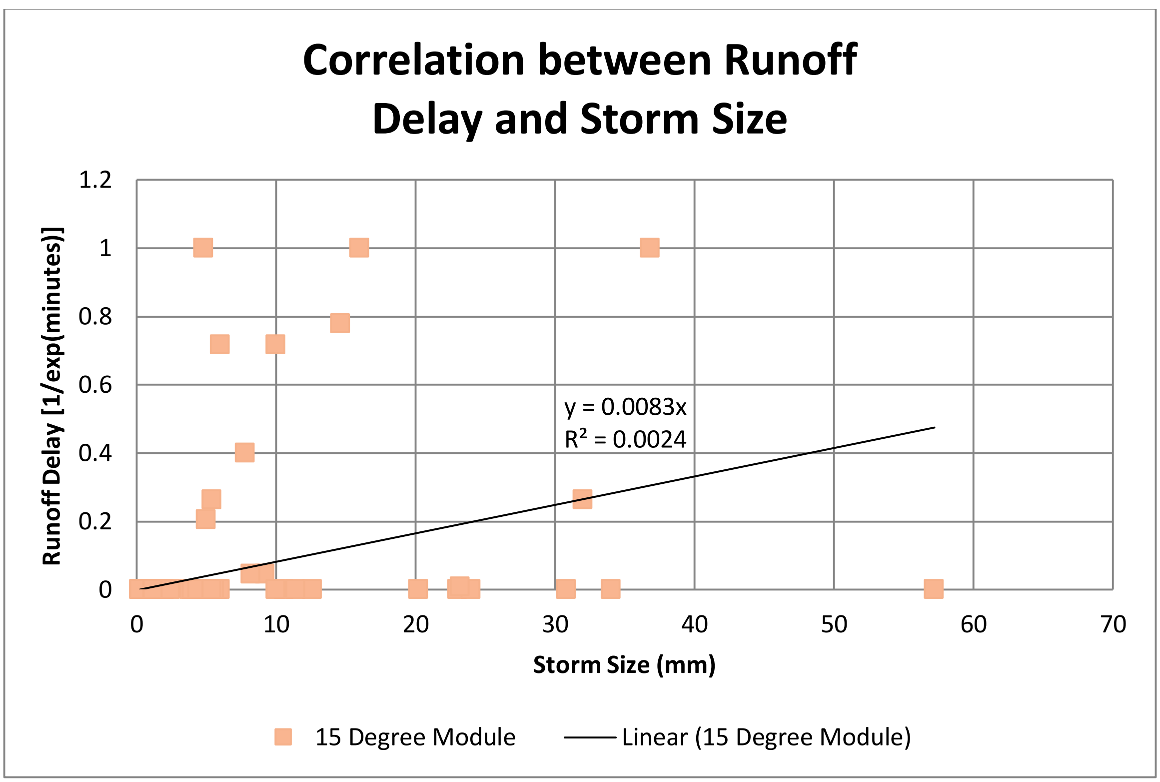

Figure 42. Correlation between Runoff Delay and Storm Size

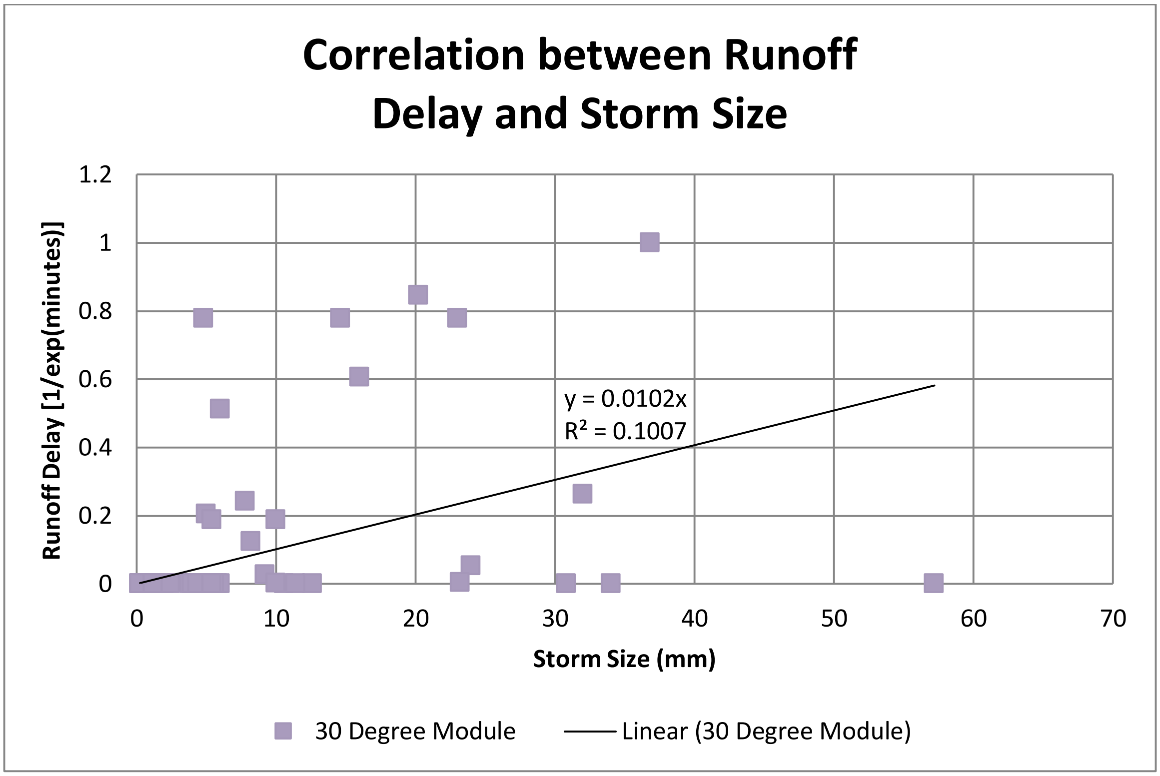

Figure 43. Correlation between Runoff Delay and Storm Size

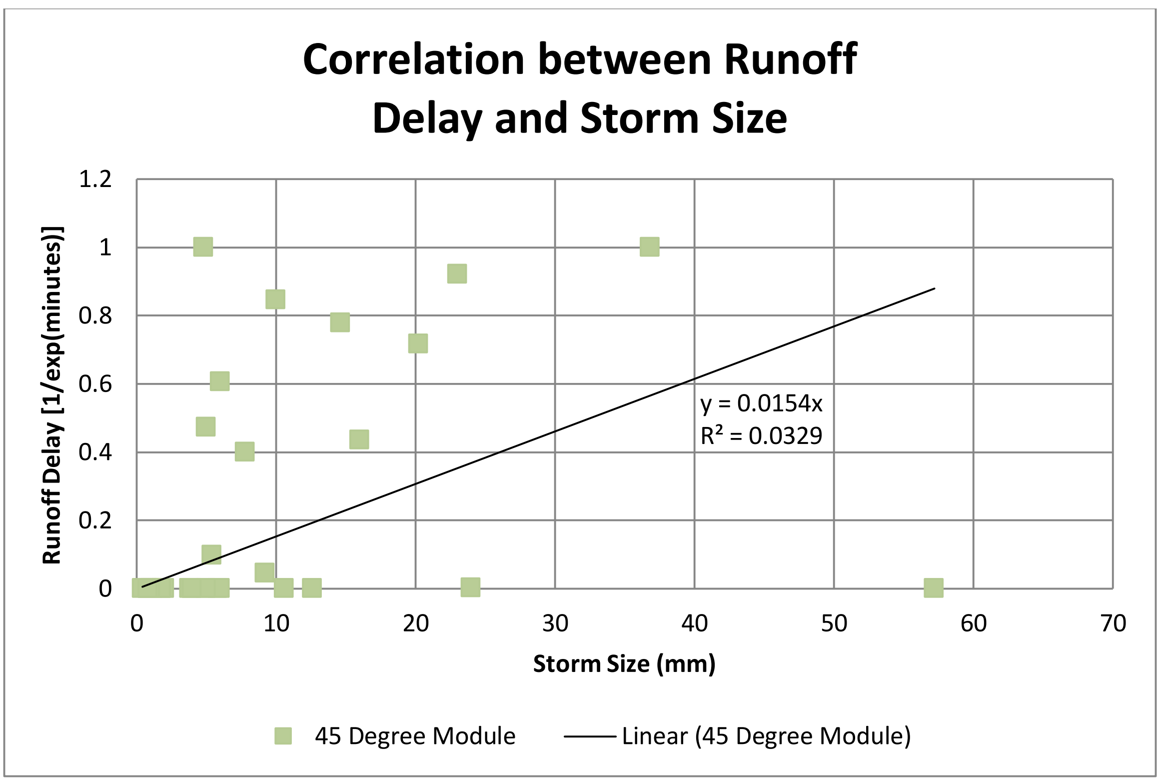

Figure 44. Correlation between Runoff Delay and Storm Size

Appendix I – Correlation between Runoff Delay and Storm Size Plots

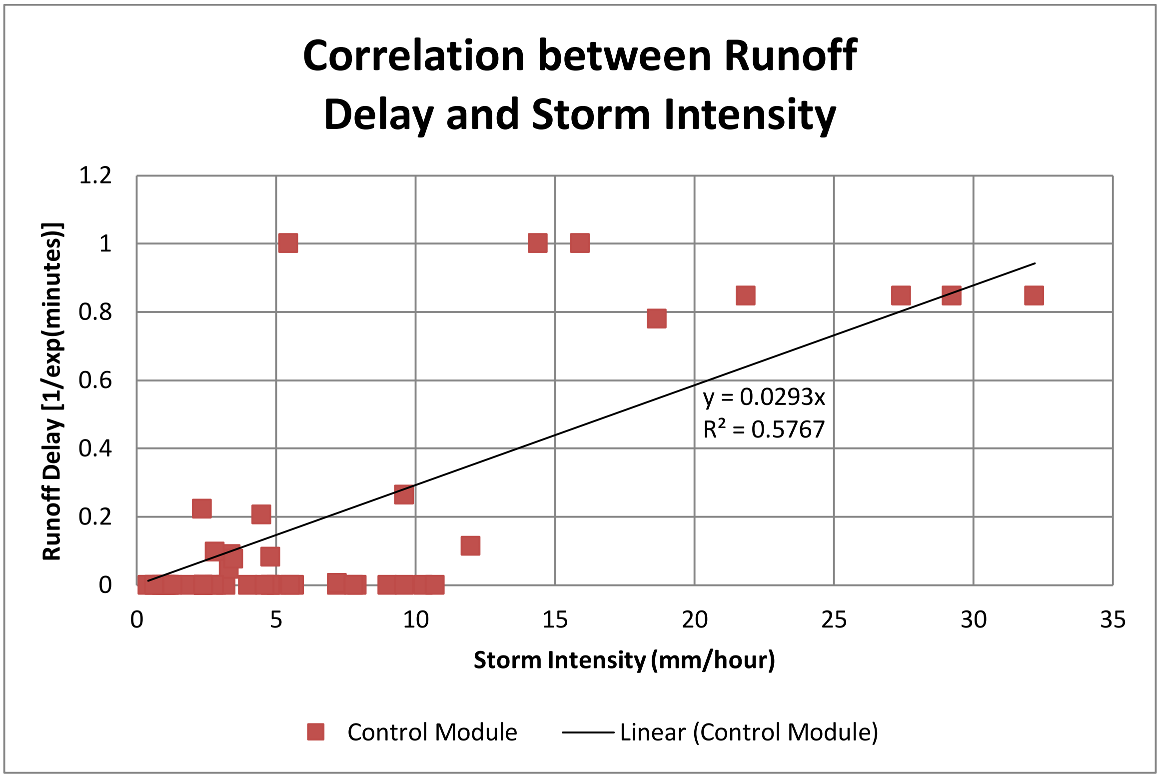

Figure 45. Correlation between Runoff Delay and Storm Intensity

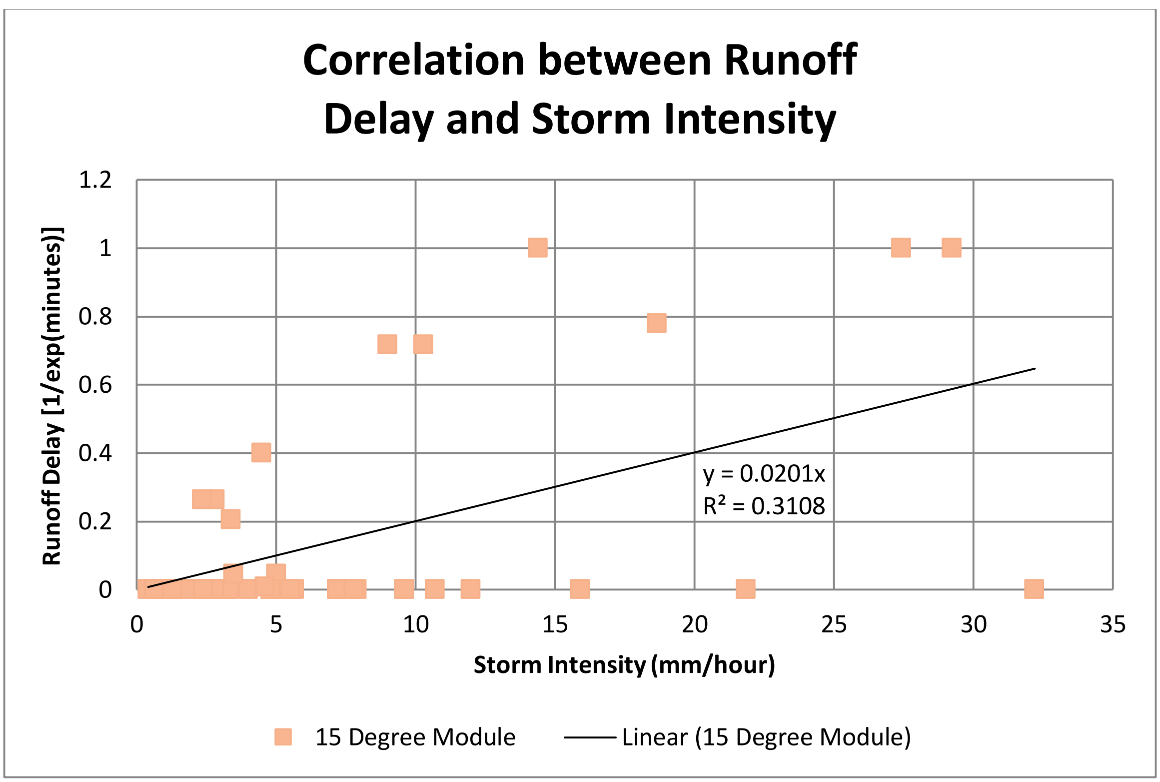

Figure 46. Correlation between Runoff Delay and Storm Intensity

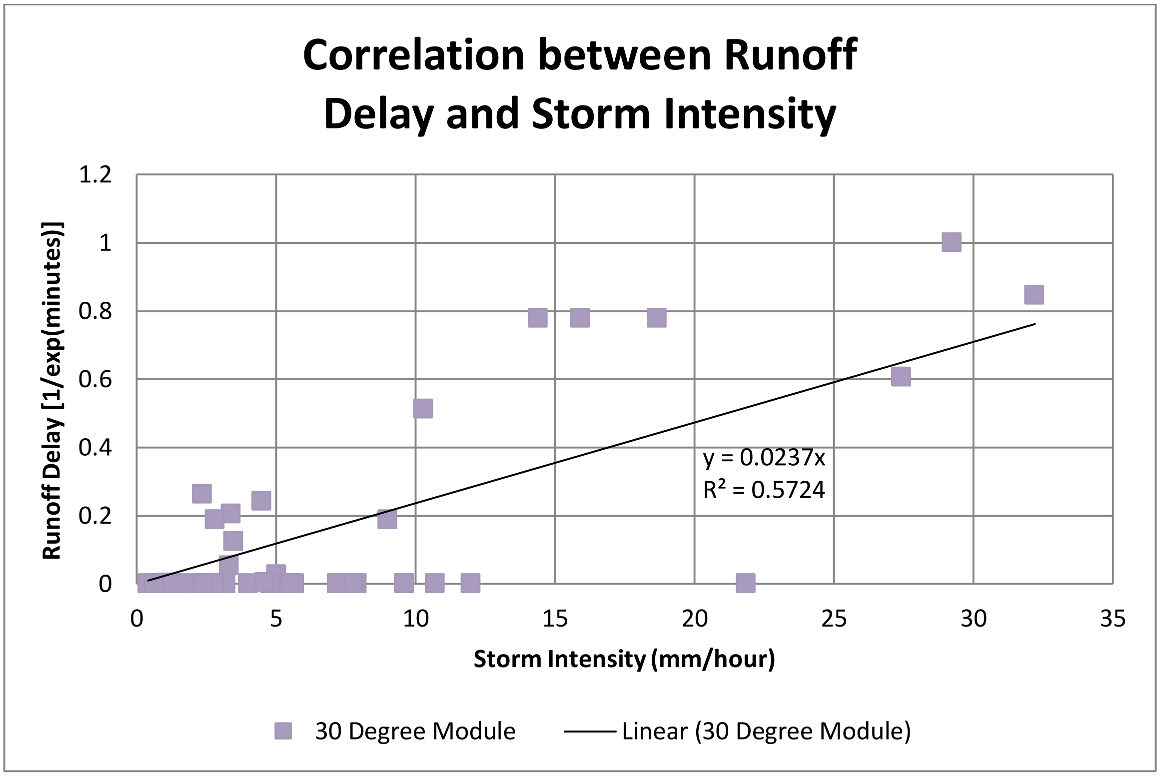

Figure 47. Correlation between Runoff Delay and Storm Intensity

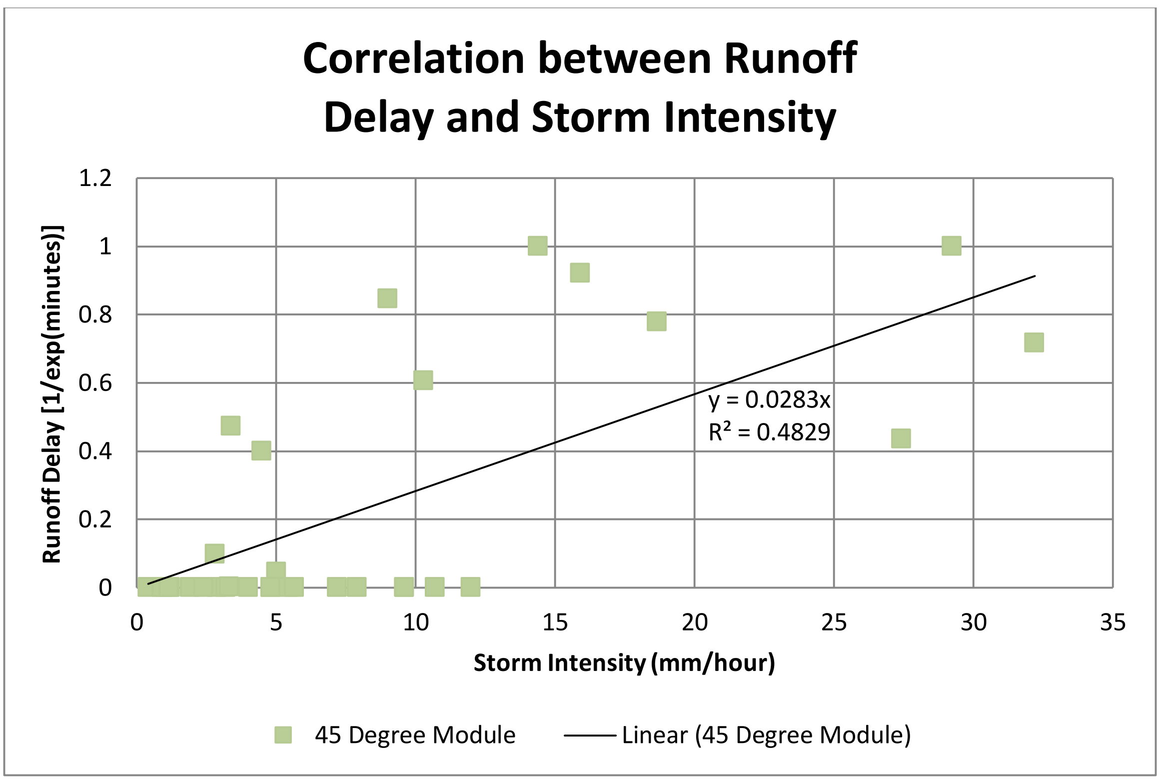

Figure 48. Correlation between Runoff Delay and Storm Intensity

Appendix J - Glossary

Absolute coverage: The percentage of plant coverage of the surface of the green roof module (Starry and Gaches 2012)

Dead load: The weight of the roof itself along with other permanent elements that make up the roof structure (Magill 2011)

EPDM: Ethylene propylene diene monomer rubber is an extremely durable synthetic rubber roofing membrane widely used in low-slope buildings (EPDM Roofing Association 2015)

Evapotranspiration: The process of water evaporating from the substrate and the water that is transpired by the plants of a green roof

Extensive: A type of green roof designed for the main purpose of sustainability; Extensive roofs usually consist of a thin layer (less than 6 in.) of soil medium and genus Sedum plants (Magill 2011)

Foliage: Clusters of leaves or flowers

Granulometric distribution: Variance of particle sizes

Green roof: "rooftops that are partially or completely covered with vegetation growing in soil medium over a waterproof membrane" (Taylor 2007)

Haydite: heat-expanded shale, clay and/or slate (DiGeronimo Aggregates LLC 2009)

Inorganic material: The component of green roof substrate that is defined as a high porosity natural mineral element such as expanded slate, shale, extruded clay, rock wool, lava or pumice, etc.

Intensive: A type of green roof designed for the main purpose of aesthetics; Intensive roofs usually consist of a thick layer (greater than 6 in.) of soil medium and a more diverse set of vegetation (Magill 2011)

Live load: Any transitory weight, including human traffic or temporary installations (Magill 2011)

Maximum load: The greatest weight a roof can hold before it fails (Starry and Gaches 2012)

Media: A material that holds the plant, provides it with nutrients, and stores water; it is usually mineral based with 0-20% organic matter, such as fertilizer (Magill 2011)

Membrane Layer: First layer of the green roof that protects the building from roots and water. Mostly bitumen or PVC membranes, reinforced with polyester, fiberglass, plastics, synthetic rubber, polyethylene, or mineral granules (Perez 2012)

Modules: A miniature green roof that is used as a basis for the design and planning of the actual green roof (Starry and Gaches 2012)

Organic material: One component of substrate of green roof that is defined as cells and tissues of soil organisms and chemical compounds from remains of plants and animals at various stages of decomposition (Nagase and Dunnett 2011)

Peak flow (rate): The maximum volume flow rate that is being drained into the system at a particular time during a rainfall (Starry and Gaches 2012)

Porosity: Measure of how much of a rock is open space - the space can be between grains or within cavities.

Re-roofing: The process of replacing all or part of the existing roof system with a new roof (Hodgson 2012)

Retrofit: A redesign of an existing structure with additional parts (Magill 2011)

Rock wool: Inorganic material made into matted fiber used especially for insulation or soundproofing, but can also be used for capillary layers in green roofs.

Saturation: The state when the green roof system absorbs a large amount of water and is filled to full capacity and unable to absorb more, adding to the system's dead weight (Luckett 2002)

Storm Intensity: Qualitative categorical measure of the rate of rainfall for a single rain event

Storm Size: Qualitative categorical measure of total rainfall for a single rain event

Substrate: Another term for "Media." A material that holds the plant, provides it with nutrients, and stores water; it is usually mineral based with 0-20% organic matter, such as fertilizer (Magill 2011)

Urban heat island effect: Built up areas, such as cities, are hotter than surrounding rural areas due to the increased amounts of impermeable and dry surfaces, such as asphalt roadways,and concrete pavements, that absorb more heat than vegetation (United States Environmental Protection Agency 2013).

Worst case scenario load: The load when the substrate is fully saturated and has an equivalent applied load of expected snow and ice. The design load must always be calculated in regards to this worst case scenario load (Hodgson 2012)